IMPROVEMENT OF JOINT SEALANT CONFIGURATION AND PERFORMANCE

A Dissertation

by

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ABSTRACT

The jointing of concrete pavement is intended to provide free movement within the concrete slab. Joint sealing material, called joint sealant, has evolved in recent decades to prevent or reduce the amount of water from rainfall events infiltrating a pavement structure. As this evolution has progressed, joint sealant practices have changed. However, current practices and their respective performances have yet to be fully documented. Therefore, it is necessary to establish a standardized approach to joint sealant evaluation, as well as investigate and assess joint sealant practices in Portland cement concrete design.

Current joint sealants are designed without consideration of the strength and shape of the bond between the concrete and sealant and its effect on stress concentration. This often results in adhesive failure within 1.5 years, much earlier than the expected service life of the joint sealant (20 years). Bond strength and stress on the interface between the sealant and joint reservoir face play important roles in adhesive failure. Therefore, in the present research, experimental bond tests and a finite element method (FEM) analysis are conducted to examine the nature of the bond at the sealant/joint reservoir interface. In addition, the stress distribution along the interface is also investigated by analyzing the geometric shape factor (SF), degree of curvature (DoC), and joint preparation conditions.

For this study, data is gathered through a literature review, survey of Departments of Transportation (DOTs), and subsequent discussions with selected agencies to determine case documentation practices. In addition, re-evaluation of the SF was conducted, and a new design factor, DoC, is introduced and explored through the FEM and experimental

analysis. With these factors, the reduction of bond strength and increase in stress at the interface may be limited, reducing the potential for early adhesive failure. This study examines the effects of moisture content on bond strength, the main cause of joint sealant failure. Sealant use in various climatic regions throughout the United States is examined, and DOTs are surveyed with regards to how they handled moisture.

As a result of this investigation, it becomes clear that some advances in the composition, design, and preparation of sealants, especially in terms of the design of and inspection methods for narrow joints, appear to conflict with established recommendations. It also appears that institutions lack the necessary tools and control protocols to facilitate the proper inspection of cleaning and joint preparation work. The effects of poor joint preparation (i.e., dirt and moisture) on joint strength and the shape of the joint sealant (i.e., SF and DoC) should be considered when designing and installing sealants. This research evaluates the effects of surface moisture on the tensile bond strength between a joint sealant and reservoir. The causes of degradation in adhesion strength are evaluated by measuring the sealant wetting angle. Finally, it is determined that the best choice of sealant may depend on climate. Those not currently preferred in wet-freeze regions may be used if accompanied by proper pretreatment and moisture control, contributing to the stable lifespan of joint sealants and concrete pavement alike.

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Contributors

This work was supervised by a dissertation committee consisting of Professors Dan Zollinger, Robert Lytton and Maryam Sakhaeifar of the Department of Civil and Environmental Engineering, Professor Reza Langari of the Department of Mechanical Engineering at Texas A&M University.

All other work conducted for the dissertation was completed by the student independently.

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1. INTRODUCTION

1.1. Background and Motivation

Concrete pavement joint performance is one of the most important issues that the concrete highway industry faces today. Over the years, highway engineers have sought to find new ways to improve joint design and longevity. Recently, the emphasis has been on the choice of joint sealant, its effect on pavement life, the role maintenance plays in joint lifespan. The bonding and shape of a sealant within a joint reservoir are major factors affecting the performance of newly constructed pavements.

Despite recent advancements in pavement design and construction quality control, challenges related to the proper installation and shaping of joint sealants continue unresolved. Questions remain regarding whether joint sealing is needed for all jointed concrete pavement applications. State agencies have many years of experience with concrete pavement, both with and without the use of joint sealants. The Wisconsin Department of Transportation (DOT) was the first highway department to stop sealing joints, specifying the use of open joints instead [1]. The agency decided that the performance was not significantly different, regardless of whether a sealant was used. After additional experience, the Wisconsin DOT began using joint sealants in lower-speed roadways with curbs and gutters, but continued using open joints on high-speed highways. In California, both sealed and open joints are used, depending on the climate in the area [2].

Conversely, most state agencies have found better performance from sealed joints and no longer allow open joints. More broadly, over the years, numerous field studies have demonstrated the value of sealing joints [2-7]. Despite questions as to whether joint sealing is necessary or preferable, it is still the cheapest and most effective way to maintain concrete pavement life. An LTPP study involving a silicone-based joint sealant in Arizona showed the overall sealant performance to be surprisingly good, with some seals being in service for over 20 years [8]. A California DOT (Caltrans) study found rubber seals in good condition after 10 years of service [9].

Such discrepancies likely stem from the joint sealant not being properly maintained, due to improper configurations and joint preparations. The present research identified frequent conflicts between recommended designs and current practices. An evaluation of current sealant configurations provided important information that will help extend joint sealant lifetimes. Furthermore, the effects of joint preparation on bond strength were evaluated to determine the optimal sealant type, considering the temperature and moisture conditions in the region. This research will help with analyzing contact angles according to the type of sealant and identifying problems associated with improving sealant choice based on climate. Finally, consideration of joint sealant practice as it relates to premature failure and improvements in joint design and preparation identified by the finite element method (FEM) and experimental study will help to reduce the controversy over whether or not a sealant should be used.

1.2. Objectives

The primary objective of this dissertation was to improve joint sealant configuration and performance. Although there are various strategies for improving the performance of in-service joint sealants used in concrete pavement, this study focuses on a stress-strain analysis based on design configuration and preparation. The objectives of this study were to:

1) Review and analyze the joint sealant configurations currently used by state agencies;
2) Document joint sealant practices to improve the serviceability of concrete pavement;
3) Evaluate the effects of the strength and shape of the bond between concrete and sealant on stress concentration; and
4) Evaluate the effects of moisture content on bond strength and contact angle.

These objectives will benefit the industry by increasing the durability and reliability of concrete pavement across the service life. Along with improved serviceability, the total cost will likely decrease due to the reduced cost of future maintenance and replacement.

1.3. Dissertation Organization

Following this introduction, Section 2 summarizes the conventional practices and previous studies on concrete joint sealants. Section 3 presents an evaluation of documented joint sealant practices for Portland cement concrete (PCC) pavement design and the joint preparation. The data were gathered through literature reviews, DOT surveys, and subsequent discussions with selected agencies. Section 4 addresses the effects of shape and bond strength on the adhesive failure of joint sealants. Stress distribution on the interface is also investigated, according to the geometric shape factor (SF) and degree of curvature (DoC). Section 5 describes an experimental study of the design and behavior of concrete pavement joint sealants. The SF and DoC were evaluated through a tensile test of joint sealants, based on their geometric characteristics. Section 6 describes an experimental study of the behavior of moisture with regards to concrete pavement joint sealants. The causes of degradation in adhesion strength were evaluated by measuring the sealant wetting angle. Finally, Section 7 provides a summary and conclusions, as well as recommendations for future research.

2. LITERATURE REVIEW

This literature review summarizes the conventional practices and previous studies on concrete joint sealants. The results of this literature review were also used to develop questions for the questionnaire described in Section 3.

2.1. The purpose of a joint

Joints in concrete pavement are primarily used to provide freedom of movement to a slab, relative to volumetric changes in the concrete that result from drying shrinkage, temperature changes, and moisture variations. Joints are designed to control cracking, minimize stresses in the pavement caused by such changes, prevent moisture intrusion, and minimize incompressible materials in the joint. Joints have always played an integral part in concrete pavement construction. The basis for joint geometry and design was to a great extent established many years ago [10].

The first specifications regarding joint placement in concrete pavement were addressed in guidelines for transverse joint spacing promulgated by the American Concrete Institute in 1914 [11]. Discontinuities presented by the use of joints in Portland cement concrete pavement are a major performance concern, since they tend to create planes of weakness in the slab [12]. In many instances, distresses often initiate and propagate at or near these joint locations. Therefore, attempts have been made to reduce the number of joints by extending joint spacing, but these measures tend to be offset by the effects of the sensitivity of the concrete to temperature changes derived from the thermal coefficient of expansion.

The use of customized curing techniques and construction methods has had some success in yielding Portland cement concrete (PCC) pavement with longer joint spacing. Field observations related to the improvement of joint patterns have been suggested as a key means of helping to avoid early distresses at joints [13].

2.2. The role of joint sealants

The purpose of a joint sealant is typically to limit the infiltration of water into the joint reservoir and underlying pavement substructure. As previously noted, joint sealants may also limit the infiltration of incompressible materials into the joint area. Unless otherwise noted, the subsequent discussion collectively considers a variety of concrete pavement joints. The components of a sealed joint (illustrated in cross-section in Figure 5.2) are the sealant (joint material), reservoir (joint well or cavity containing the sealant), and backer rod (a compressible material that fits into the joint reservoir). The backer rod helps to establish a suitable sealant shape factor (SF) and prevent three-sided adhesion. The SF is defined as the ratio of the sealant's depth to width that is used to minimize stresses within the sealant.

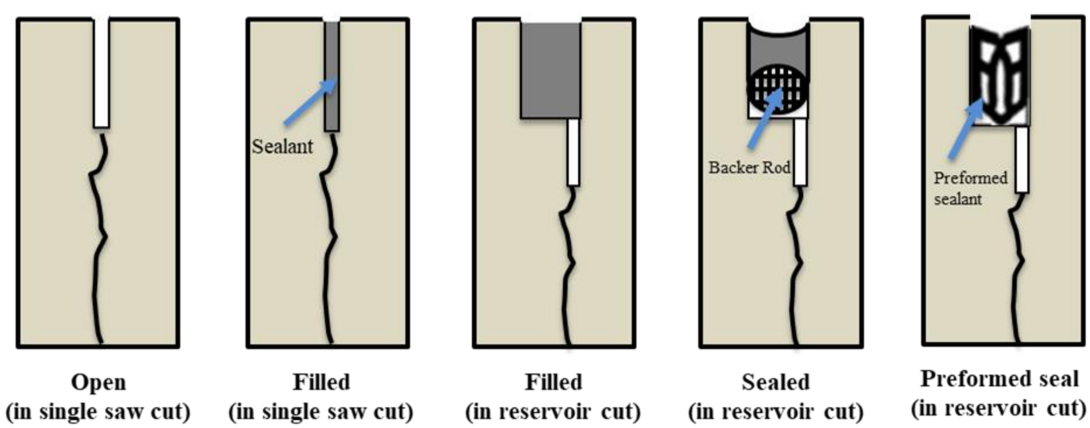


Figure 2.1. Examples of formed-in-place (liquid) and preformed sealants.

Hot rubberized asphalt products usually have strong sealing characteristics, are fairly low in cost, and offer substantial versatility; however, when they age, water penetration becomes possible, especially as flexibility and bonding along the seal/joint wall interface decrease over time [14]. Most state Departments of Transportation (DOTs) use certain kinds of asphalt to seal and reseal cracks and joints. However, the possibility of failure increases if the sealant is not properly installed [15]. If properly installed, a hot-pour joint sealant can have a lengthy lifespan.

A study by the Federal Highway Administration (FHWA) found that sealants with a total efficiency of 75% lasted approximately nine years [16]. This study also showed that the service life of a sealant can vary and might not always reach its average lifespan. Various factors such as installation, climatic conditions, traffic level, etc., play a role in the serviceability of a joint sealant. The study included the Strategic Highway Research Program [17] H-106 maintenance experiment and FHWA Long-Term Monitoring of Pavement Test Sites [16]. Another sealant study conducted by the California Department of Transportation (Caltrans) explored the field of sealants used by both Caltrans and industry. Their examination showed that in general, rubber seals with 10 years of service were still in good condition [9].

More recently developed silicone-based materials offer improved durability and coupling with concrete. This type of sealant is easier and safer to apply than asphalt sealants. Silicone sealants usually have excellent adhesive properties and less sensitivity to aging and temperature, and thus a lesser impact on strength. Silicone sealants are more expensive than hot-pour asphalt, though silicone has a longer service life [18, 19].

One study of silicone-based joints in Arizona showed excellent joint seal system performance over a very long period of time (approximately 20 years) [8]. The concrete pavement test site of the Arizona Special Pavement Study (SPS-2) was installed in 1993, with 12 long-term pavement performance and nine Arizona Department of Transportation test sections. The assessment of the joints and seals found that the overall performance of the joint seal system SPS-2 was surprisingly good, with seals in place for 20 years for a truck lane carrying approximately 31 million equivalent single-axle loads [8].

2.3. Types of Sealant Material

There are currently three primary types of sealant used for rigid pavement applications: asphalt-based (hot-pour), silicone, and compression. Historically, the most commonly used sealant material for concrete pavement joints has been hot-applied asphalt-based materials. However, silicone-based sealants (ASTM D5893) and pre-formed compression sealing materials (ASTM D2628) are recognized as being more suitable for use in rigid pavements, and have become the preferred alternative of a large number of state DOTs [20].

- **Hot-pour sealants**: Hot-pour sealants were the first type of sealant to be developed. Hot-pour sealant is made from a combination of polymers, asphalt plasticizers, and reinforcing fillers. Each manufacturer has different combination of the components with a different proportion for their products. Manufacturers have improved their adhesive qualities and they give excellent extensibility to low-module materials [2]. For proper installation, the materials require heating, usually between 350°F and 400°F (177°C to 204°C). The contractor and agency personnel are expected to ensure that the sealant is installed at the required temperature.

- **Silicone sealants**: Silicone sealants are polymers in liquid form and are field-poured. Pavement specifications for using these products were developed in the 1970s [21]. The installation procedures are similar to those for other formed-in-place sealants. Silicone sealants consist of self-leveling (ultra-low modulus) and non-sag (low modulus) types. With regards to their elastic properties, silicone sealants are ideal for climates with broad temperature ranges. Most silicones develop a low elastic modulus, allowing for good extension and compression recovery [2].
- **Preformed (Compressive) Sealants**: Manufacturers introduced preformed compression seals in the early 1960s. They differ from other sealants because they are ready for application without field heating, mixing, or curing. Unlike formed-in-place sealants that undergo compression and stress, preformed compression seals are designed for compression only after deployment. The effectiveness of the preformed sealant depends solely on the seal's lateral pressure over its lifespan [2, 5, 22].

Silicone and preformed compression seals typically outperform asphalt-based sealants for concrete pavement but are also proportionally more expensive.

2.4. Material Selection

When planning a joint sealing project, one of the primary design activities is selection of the appropriate sealant material. Material selection depends on a number of factors, typically including the following:

- Climate conditions (at the time of installation and during the life of the sealant)
- Joint/crack characteristics and spacing/density
- Traffic level and percent of trucks
- Material availability and cost

The above list includes factors that govern the range of movement that the joints/cracks and sealant will experience. Because sealant materials have different extension properties, one must be selected that is capable of accommodating the maximum anticipated joint opening [2]. Other factors are discussed below, such as the different types of materials typically used as joint sealants, critical performance material properties, and cost considerations.

2.4.1. Selecting Sealant Materials

Many factors should be considered when selecting a suitable joint sealant material, including the type of joint and expected joint movements, climate (which impacts required extensibility), bond compatibility with the substrate materials (e.g., concrete only or concrete and asphalt), chemical compatibility with the substrate materials (e.g., the sensitivity of some silicone sealants to limestone aggregate), the need for rapid sealant curing, resistance to fuel spills or jet blasts, material and installation costs, and expected performance life [22]. The use of longer-life sealants should be considered even if they entail an additional initial cost because joint sealant maintenance is often deferred (or ignored) [22].

Once a sealant material is selected, an appropriate reservoir design should be developed for optimum performance of the sealant material. For formed-in-place sealants, this decision may also involve the selection of a backer material (as appropriate, depending on the type of application) to prevent the sealant from displacing into the joint. Furthermore, the initial material selection may involve consideration of the following:

- Joint movement behavior (a combination of climate and joint spacing) [23]
- Traffic volume and traffic characterization [12]
- Lifecycle cost [14, 18, 19]

2.4.2. NTPEP Database

The Transportation Product Evaluation Program (NTPEP) database was established by the American Association of State Highway and Transportation Officials (AASHTO) in 1994 as a technical service program. Under the NTPEP evaluation program, PCC joint sealants, both hot-poured and cold-applied, are field and laboratory tested according to a variety of ASTM-specified test methods. The NTPEP database combines professional and physical resources of AASHTO member departments, allowing for the evaluation of materials, products, and devices of common interest to be used in highway and bridge construction. The database simplifies the product evaluation process, provides cost-effective assessments, and reduces the overlapping of state DOT efforts [24].

2.5. Joint Sealant Design Factors

Factors related to joint sealant design, including sealant movement and geometry, were reviewed as reported in the literature. The purpose of jointing concrete pavement is to control cracking and provide concrete expansion and shrinkage motion according to temperature and moisture changes. Sealed joints generally restrict water ingress into joint reservoirs and substructures. The components of a sealed joint, illustrated in cross-section in Figure 2.2 [2], are the sealant (joint material), reservoir (joint well or cavity containing the sealant), and backer rod (a compressible material that fits into the joint reservoir).

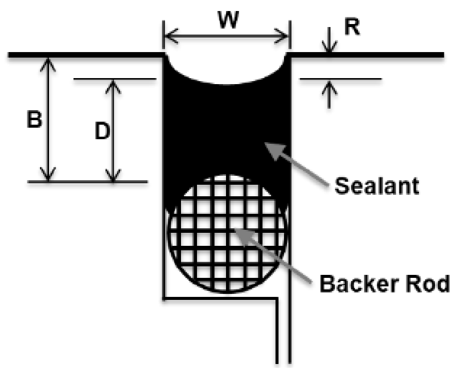


Figure 2.2. Typical reservoir configuration for liquid sealant.

2.5.1. Reservoir Size and Joint Movement

Reservoir size is an important consideration for facilitating the proper installation and functioning of a sealant. The width of the reservoir should be wide enough to facilitate thorough cleaning of the sawcut surface, enhancing adhesion between the sidewalls of the joint reservoir and sealant. A sealant must be capable of accommodating the anticipated joint opening and closing due to temperature changes [2].

Because the width of the joint sealant varies according to temperature-induced movement, a suitable reservoir size should be selected to accommodate the movement of an adjacent slab, allowing it to remain within permissible strain limits. However, material and climatic variability should be accounted for to avoid overextension and damaging of the sealant. Variability can be addressed using probabilistic models to estimate a range of movements for a given combination of concrete materials and joint spacings [25].

2.5.2. Sealant Geometry

A reasonable engineering approach to modeling sealant behavior is to take into account the effects of joint width, depth, and curvature. The shape factor (SF) (defined in width/depth) is very important when determining the geometry of a sealant [26], an essential factor in current engineering practices for joint sealant design [26-29].

Researchers have studied rectangular sealant joints using the finite element method (FEM) of analysis [30-32]. One project, the first time FEM analysis was used to examine the stress distribution in a joint sealant, involved laboratory static and cyclic testing. Myers [33] studied the effects of joint shape on sealant performance and stress distribution within the sealant. Another recent study also investigated stress distribution, along with the joint reservoir and sealant interface, finding that the latter varied with the sealant geometry (i.e., SF). A new parameter, referred to as the degree of curvature (DoC), was also evaluated. Researchers suggested that premature adhesive failure could be limited by increasing SF to reduce stress generation in the overall section, or by increasing the DoC to reduce stress concentration along the interface [7].

Figure 2.2 shows the typical sealant configuration, illustrating the dimensions associated with the SF that are critical to the long-term success of poured sealants. An SF equal to or greater than 1 induces lower stresses in the joint sealant than does an SF below 1. Lower or reduced internal stresses resulting from proper shape factors minimize adhesive and cohesive loss [2]. Table 2.1 lists reservoir and sealant dimension recommendations for hot-pour and silicone sealants. For hot-pour materials, filling the reservoir flush with the pavement surface is preferred because traffic keeps the materials pliable, and studies have indicated that this practice reduces noise. For silicone sealants, SF design should include recessing the sealant below the pavement surface from ¼" to 3/8" (6 to 10 mm) to prevent tire contact.

Table 2.1 Typical Reservoir Dimensions [2]

Hot-pour sealant	**Silicone sealant**
R = 0.0" (0 mm) Flush Fill; No Recess	R = Sealant Recess ¼" to 3/8" (6 to 10 mm)
B = Depth to Top of Backer Rod = Min. of 5/8"	B = Depth to Top of Backer Rod = Min. of 5/8"
D = Nominal Sealant Thickness (Depth) = Min. ½"	D = Nominal Sealant Thickness (Depth) = Min. ¼"
W = Joint Reservoir and Sealant Width = Min. ¼"	W = Joint Reservoir and Sealant Width = Min. ¼"
Shape Factor (W/D) = 1/1	Shape Factor (W/D) = 1/1 to Max. 2/1

SF recommendations of 1 to 2 for silicone materials and 1 for hot-pour sealants are based on the material's cross-section rather than the associated bond conditions [2]. The effect of using a narrow joint configuration is largely unknown. Optimizing the SF relative to the type of material and degree of bond at the sealant-joint reservoir interface is a key item of interest.

2.5.3. Surface Configuration for Joint Sealing

Sealants can be placed in a joint in several different configurations, as shown in Figure 2.3 [34]. These configurations are described below:

- Most silicone sealants are placed in a recessed configuration, where the top of the sealant in the reservoir is roughly 0.12” to 0.25” below the pavement surface. This configuration prevents the sealant from being removed under high traffic conditions. Silicone sealants should be placed only in a recessed configuration [2, 7].
- Flush-filled configurations apply only to hot-pour sealants, where the sealant is placed flush with the pavement surface. This configuration is recommended by certain manufacturers because it eliminates a reservoir area for incompressible materials to collect and helps the sealant remain more ductile, due to it being subjected to the kneading action of passing tires [34].
- Over-banded configurations involve slightly overfilling the reservoir. While this method maximizes the bonding surface area between the sealant and pavement, it is susceptible to snowplow damage and can negatively affect ride quality [35].

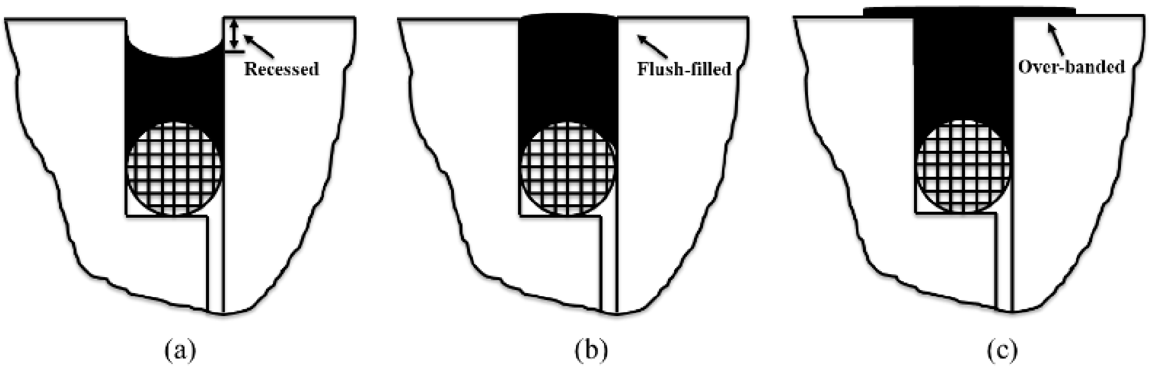


Figure 2.3. Sealant surface configurations.

2.6. Joint movement and allowable strain

The size of the reservoir determines the proper installation and movement of the sealant. The size of the reservoir is what defines the size of the sealant and accommodates the joint movement within the expected range of allowable strain resulting from thermal expansion.

2.6.1. Reservoir Size and Joint Movement

Reservoir size is an important consideration when pursuing the proper installation and functioning of a sealant. The reservoir should be wide enough to facilitate proper cleaning of the sawcut surface, which will enhance adhesion between the sidewalls of the joint reservoir and sealant. [2].

A sealant must be capable of accommodating the anticipated joint opening and closing that results from temperature changes. Joint movement estimates have typically been made using Eq. (5.1)

Because the width of the joint sealant varies according to the temperature-induced movement, a suitable reservoir size should be selected to accommodate the adjacent slab's movement while remaining within the allowable strain limits. However, material and climatic variability must be accounted for to avoid overextension and sealant damaging [25].

2.6.2. Maximum Allowable Strain

Different sealant types can withstand different stress-strain levels. The maximum allowable strain of an extreme sealant fiber depends on the amount of sealant elongation (or joint opening) and the SF. Most hot-pour liquids can withstand about a 20% tensile strain of their initial width for the service life. Silicone and some other low-modulus materials can theoretically undergo up to 100% strain. However, manufacturers recommend using a total strain of no more than 50%, and ideally only 25% for a design in order to limit the debonding potential [3].

In previous studies [27, 28, 36], the stress and strain analyses of sealants have conservatively limited the stress level of a joint seal to between 25% and 50%. However, it appears that these limits are largely empirical and lack theoretical justification. Much of the past sealant research has focused primarily on internal stress conditions and less on the tendency for fracture between the sealant and joint reservoir wall.

2.7. Joint Preparation Practice

In recent years, states have adopted a greater variety of joint sealing practices for jointed pavements, based on local preferences, climate, and traffic conditions. The driving force behind these variations seems to be a decrease in sealing cost while supposedly maintaining the same level of performance. Traditionally, transverse contraction joints in PCC pavement are used, according to the steps outlined below [2]:

- Step 1. Sawcut widening: This involves sawing/widening the shape of the reservoir for sealant installation. The reservoir saw cut removes any raveling caused by the initial cut and provides the proper dimensions for the sealant.
- Step 2. Cleaning: Cleaning is the most important aspect of joint sealing. Manufacturers suggest similar cleaning procedures for all formed-in-place sealants. The performance of formed-in-place sealant products is predicated on proper preparation and cleaning procedures.
- Step 3. Backer rod installation: The backer rod should be compatible with the sealant and sized to be about 25% to 50% greater than the reservoir width. Backer rods are inserted easily with a double-wheeled steel roller that forces them uniformly to the proper depth.
- Step 4. Cleanliness check: Installation of the sealant should not proceed until the reservoir walls are free from dust.
- Step 5. Sealant installation: Installation requirements vary slightly for each sealant type. Manufacturers recommend some curing or cooling time for formed-in-place sealant materials and typically suggest limits on air and pavement temperatures for installation.

Adhesion loss is the most common distress occurring in joint sealants, due to insufficient joint preparation [5, 37]. In order for the sealant geometry to make a difference in performance, the sealant must be fully bonded to the wall of the joint reservoir [38].

One key to the successful performance of a joint sealant is the effective inspection of the reservoir edge before installation. Previous research has indicated that a lack of emphasis on cleaning and drying is a major problem affecting sealant bonds [6, 7, 39, 40]. Appropriate emphasis on quality assurance and inspection would maximize sealant bond strength and greatly improve not only the joint sealant but also the concrete pavement's performance lifespan [2, 5, 7, 41]. Reservoir wall faces require thorough cleaning and drying to ensure sealant adhesion and long-term performance.

2.7.1. Joint Preparation Methods

The key to the successful performance of a joint sealant is effective inspection of the reservoir before installation. Previous research has indicated that a lack of emphasis on cleaning is a major problem affecting sealant bonds. Appropriate emphasis on quality assurance and inspection maximizes sealant bond strength and greatly improves not only the joint sealant, but also the concrete pavement performance life [2, 5, 7, 41].

Reservoir wall faces require thorough cleaning and drying to ensure sealant adhesion and long-term performance. Proper cleaning involves mechanical action (such as sandblasting, air blasting, hot air blasting, and wire blasting) and pure water flushing to remove contaminants [42].

2.7.2. Cleanliness Inspection Methods

There are various ways in which joint reservoirs can be assessed for cleanliness [2, 3].

- Visual inspection: The inspector visually supervises the reservoir for proper cleanliness.

- Finger test: With a finger and cloth, an inspector simply wipes the reservoir sidewalls to check for any traces of dirt and dust. However, this method is only feasible for wider joint reservoirs.
- Wipe test: The wipe test captures the relative amount of concrete dust, slurry, and contaminants on the reservoir walls. The procedure requires that a clean black cloth be used to wipe the surface of the joint to determine the presence of contaminants. It is important that the inspector handle the cloth carefully to avoid contaminating it with debris from the surface. This process was developed by Wiss, Janney, and Elstner Associates and has been adopted by the American Concrete Pavement Association (ACPA) as a standard quality control test [43].

2.7.3. Studies on the Effects of Moisture on Adhesives

Conventional construction sealants, including polysulfides, polyurethanes, epoxies, and acrylics, are known to be sensitive to moisture. The properties of the polymer can degrade with moisture, an effect of hydrolysis that lowers the bond strength and can cause cohesive failure [44]. It has also been shown that the elastic modulus of an epoxy adhesive decreases as the water uptake (or concentration) of the material increases [45].

More problematically, interfacial fracture between a sealant and a substrate, a condition that usually occurs before a sealant fracture, is accelerated by moisture content. For example, interfacial fracture toughness between an epoxy adhesive and substrate (copper) has been shown to decrease with increasing water concentration within the epoxy [45]. This is a consequence of the existence of water on the surface or at an interface between an adhesive and substrate. Water can be trapped in between and prohibit good contact of the adhesive with the substrate surface. Even at an elevated temperature, trapped water will be vaporized and expand, causing delamination [46].

Lastly, certain substrates, including wood and other water-sensitive substrates, can take on water, and as a result, modify their surface geometry to be more hydrophobic. This reduces the contact surface between a sealant and substrate. Hydration and corrosion are other problems with metallic substrates when moisture is present on the substrate surface [44].

2.7.4. Studies of the Effects of moisture on the Bond Strength of Joint Sealants

The South Dakota DOT reported that between 1984 and 1990, a Sioux Falls SD test pavement experienced widespread adhesion failure, which was demonstrated through joint pumping during and after rain events. The study was conducted to identify the adhesion failure mechanism manifested in silicone joint sealants and recommend appropriate changes to ensure acceptable sealant performance. The report concluded that high moisture conditions on the concrete reservoir walls were probably present during installation of the silicone sealant, resulting in a high degree of adhesion failure. This was verified from field surveys and an analysis of laboratory experimental data [47].

The bond strength of a joint sealant to surface concrete is a function of its moisture content. However, direct measurement of the moisture content of a concrete wall surface under field conditions is complicated [48, 49]. Studies are needed to find ways of predicting the strength of adhesion by measuring moisture, which would be more suitable in field situations. One study showed that the moisture content of concrete was a function of the bond strength of the sealant. The bond strength was reduced by 35% as the moisture content increased from dry (1%) to wet (5%) [6]. Most recent research has emphasized that both moisture and dirt on the interface between concrete and a silicone sealant significantly decrease bond strength. Adequate joint preparation criteria are needed to standardize bond performance [7].

The bond strength of the joint sealant to the surface concrete is a function of its moisture content. However, direct measurement of the moisture content of a concrete wall surface under field conditions can be complicated [48, 49]. Additional research is needed to predict the strength of the bond by measuring moisture according to a means more suitable for field situations.

3. EVALUATION OF CURRENT JOINT SEALANT DESIGN AND PREPARATION PRACTICES FOR CONCRETE PAVEMENT

3.1. Section Summary

The main purpose of sealing joints in rigid pavement is to prevent or limit the intrusion of incompressible materials and reduce the amount of water that penetrates the pavement structure; such intrusions can cause erosion, a loss of support for subbases, and other water-related problems. The pavement joint sealing material called joint sealant has evolved in recent decades. As this evolution has progressed, joint sealing practices have changed. However, current practices and their respective performances have yet to be fully documented. Therefore, it is necessary to establish a standardized approach to joint sealant evaluation, as well as investigate and evaluate joint sealant practices in PCC pavement design. For this study, data were gathered through a literature review, a survey of Departments of Transportation (DOTs), and subsequent discussions with selected agencies to determine their case documentation practices. DOTs in 41 out of the 50 US states (82%) responded to a questionnaire addressing joint sealant practices for concrete pavement. As a result of this investigation, it is clear that some advances in the composition, design, and preparation of sealants, especially in terms of design and inspection methods of narrow joints, appear to conflict with established recommendations. It also appears that institutions lack the necessary tools and control protocols to facilitate the proper inspection of cleaning and joint preparation work.

3.2. Introduction

In recent decades, Portland cement concrete (PCC) pavement joint sealing materials have evolved alongside the development of new joint sealing practices. Some of this progression has concerned the design and preparation of sealants, especially the use of narrow joints, which seems to contradict long-established recommendations [12, 17]. There also appears to be significant non-uniformity and inconsistency in terms of joint sealant selection. Even though joint sealing practices have long been established, the effect of deviation from the norm in terms of performance has not yet been properly documented. Furthermore, questions exist as to the efficacy of certain joint sealants. Thus, there is a need to establish a standardized approach to joint sealant selection, as well as tools to assess the effects of sealant performance on a given PCC pavement design.

The objective of this research is to document current practices regarding design and joint preparation of joint sealants used with PCC pavement. This study shows the current status of practices and specifications related to the use of joint sealants in concrete pavement construction and identifies potential problems. Information for this research was collected through a literature review, a survey of state Departments of Transportation (DOTs), and follow-up discussions with selected agencies. Information gaps are also identified, and suggestions made for future research to address those gaps.

3.3. Current Joint sealant practice

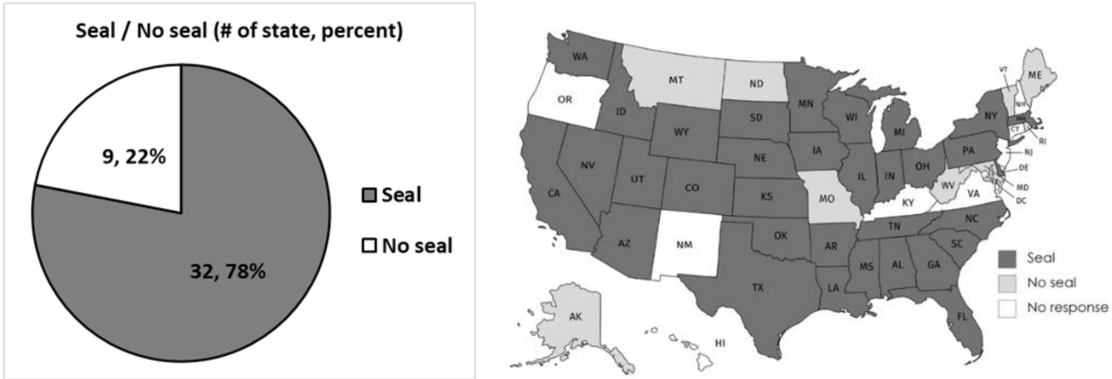
This research developed a questionnaire to obtain information related to DOT joint sealant specifications and procedures. The questionnaire was configured to identify agencies who used and had experience with joint sealing and who could be contacted for follow-up inquiries to obtain additional information on sealant performance. The questionnaire was issued in the form of an online survey, allowing for direct input from the participating agencies.

The survey questionnaire was prepared to investigate the joint sealant practices of state DOTs in the United States. The composition of the questionnaire was configured such that the practices of different states would be reflected with respect to joint sealant design and joint preparation practices.

A draft of the questions was written that classified question groups to identify current joint sealant practices. Through the literature review, detailed questions were developed to address a comprehensive scope. Elements were revised and supplemented by consulting the literature review and current standardized specifications. Questions were also developed to identify potential problems with joint sealant execution and determine how DOTs addressed them. Joint sealant experts, relevant researchers, and a National Cooperative Highway Research Program (NCHRP) committee reviewed whether the survey was appropriate for identifying the current state of and potential problems with sealant use.

3.3.1. Usage of Joint Sealants in the US

Agencies from 41 out of the 50 states (82%) responded, as shown in Figure 3.1. Thirty-two states (78%) out of the responding 41 used joint sealants, while the other nine indicated they used alternatives to joint sealing (six states) or did not use concrete pavement (three states). The nine states that did not use joint sealants were in the northern freeze area, as shown in Figure 3.1.



(a) Results of responses *(b) US map of joint sealant use on concrete pavement*

Figure 3.1. Survey Questionnaire Results.

Thirty-two states were asked about their sealant usage. Hot-pour sealants were the most popular, as shown in Figure 3.2. Only about half of the states used silicone sealants, including non-sag and self-leveling silicone sealant types. The questionnaire was formulated to determine the practices associated with each type of sealant used. For states that did not install joint sealants, the survey asked for details of alternatives employed, as well as problems with performance in the joints of their concrete pavement.

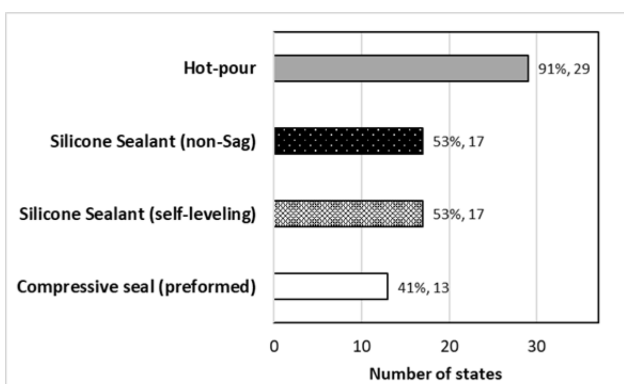
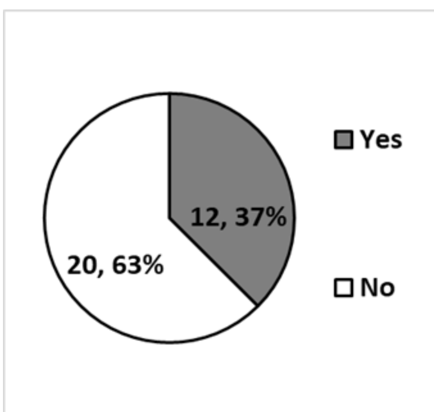
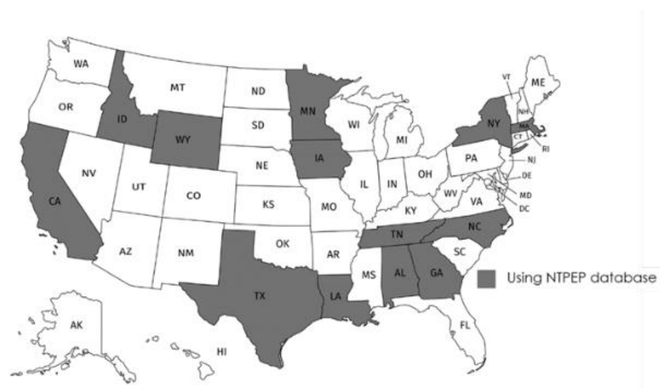


Figure 3.2. Types of joint sealant used (multiple selections).

The survey queried respondents regarding their use of NTPEP data to obtain integrated information on the joint sealants they used (product, placement, and material test information, and performance data for each joint sealant). This database provides the tools necessary for agencies seeking to report and analyze current and past sealant usage. It allows for dynamic queries regarding multiple sealant products and offers the ability to directly compare products according to established specifications and inspection requirements. The database represents a compilation of manufacturer test data on specific sealants, and often includes individual agency test data, as well. The results from the survey indicated that 12 states used the data available in this database, but primarily for quality control (see Figure 3.3). No one indicated using the database for reasons related to regional characteristics.



(a)



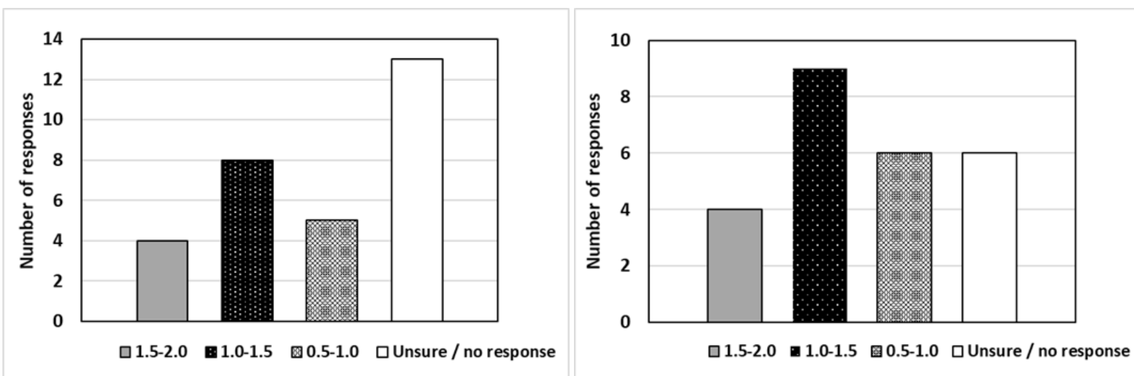
(b)

Figure 3.3. (a) Results of responses and (b) US map of NTPEP database usage.

3.3.2. Designs for Joint Sealants

The cross-section of a joint sealant changes during expansion and contraction of the concrete. Joint movements induce strain within the sealant and stress along the sealant/reservoir bond line. These material responses may become excessive if the SF is not appropriately selected/controlled. Although different formed-in-place sealant materials can withstand various levels of extension (and strain), to some degree all sealants are affected by joint movement. Joint sealant reservoir dimensions are as shown in Table 2.1.

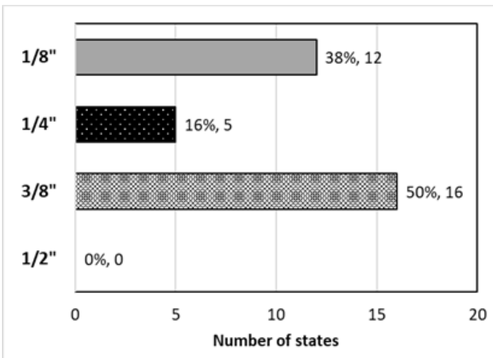
The results of the SF survey for both hot-pour and silicone sealants are shown in Figure 3.4. Over half of the states were found to be unsure or did not respond regarding practices related to sealant dimensions. The SF is critical to the success of materials intended for use as sealants, and not just as fillers.



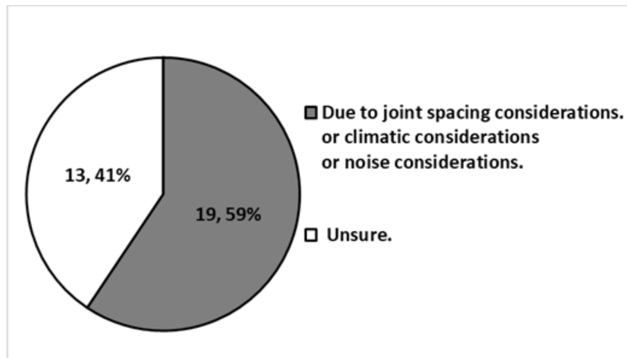
(a) *(b)*

Figure 3.4. SF range: (a) hot-pour and (b) silicone.

The minimum width of joints that state agencies are currently adopting is becoming very narrow, as shown in Figure 3.5. If joint widths of 3/8", 1/4", 1/8" are used for sealant placement, then according to ACPA guidance (see Table 2.1), hot-pour sealants should be placed at thicknesses of 3/8", 1/4", and 1/8", respectively. For silicone sealants, thicknesses should be 3/8" to 3/16", ¼" to 1/2", and 1/8" to 1/16", respectively. The latter thicknesses, if actually used under field conditions, would naturally raise concerns about the durability of the sealant, about which little guidance is available. Clearly, there appears to be a trend in the design practices currently utilized by DOTs with regards to SF and the minimum dimensions of joints being built into projects. Certainly, a reconsideration of design guidance for narrow joints not conforming to the practices recommended by the ACPA may be in order.



(a)

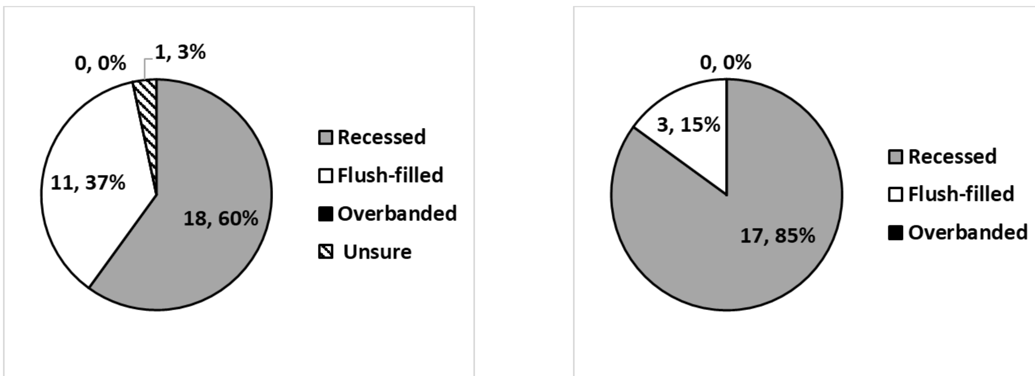


(b)

Figure 3.5. (a) Typical reservoir widths (multiple selections) and (b)reasons for using these widths.

A sealant can be placed in several different configurations, such as recessed, flush-filled, and over-banded. The use of any of these configurations (which depends on the sealant type) may limit the potential for a sealant to be removed under high traffic conditions or reduce noise (i.e., “tire slap”) from passing vehicles. Most silicone sealants are placed in a recessed configuration, where the top of the sealant in the reservoir is roughly 0.12” to 0.25” below the pavement surface. This configuration prevents the sealant from making direct contact with the wheel load in high traffic conditions. Silicone sealants should only be placed in a recessed configuration**.** The survey was conducted to determine what configurations were being installed for each joint type.

In the case of hot-pour sealants, the results of the survey indicate that unlike what was proposed by the ACPA in 2018 (flush-filled), 60% of the states installed hot-pour sealants with a recessed configuration, as shown in Figure 3.6. However, in the case of silicone sealants, most (85%) of the states installed the sealant in accordance with ACPA recommendations.



(a) Hot-pour sealant *(b) Silicone sealants*

Figure 3.6. Joint sealant surface configuration

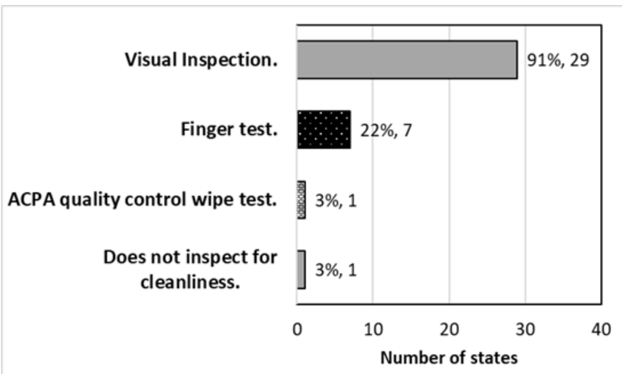
3.3.3. Joint Preparation

3.3.3.1. Joint Reservoir Cleaning Method

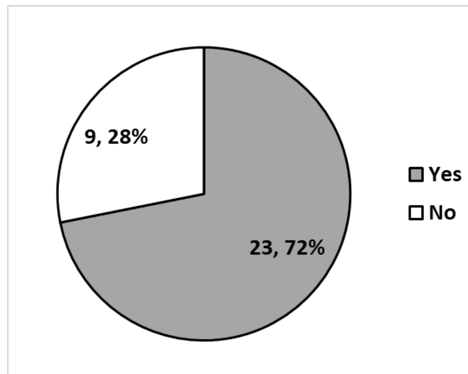
The survey contained questions regarding the method of cleaning and preparing a saw cut for sealing. The responses showed that agencies were cleaning multiple times and in various ways (air blasting, wire brushing, sandblasting, etc.). However, practices and specifications for cleaning practices seemed to vary widely from state to state.

3.3.3.2. Joint Preparation Inspection

The survey included a few questions on the inspection of joint preparation operations prior to installation of the sealant. Inspection assures that the reservoir is adequately clean. There have been recent developments in methodologies for objectively evaluating joint reservoirs. According to the survey and illustrated in Figure 3.7, most states attempted to manage cleanliness and moisture in joint reservoirs primarily through visual inspection. The ACPA-recommended quality control wipe test was only used in one state. As previously indicated by responses related to joint reservoir width, most joint reservoirs are so narrow that it is nearly impossible to check cleanliness by a visual inspection or use of the finger test method.



(a) Inspection method

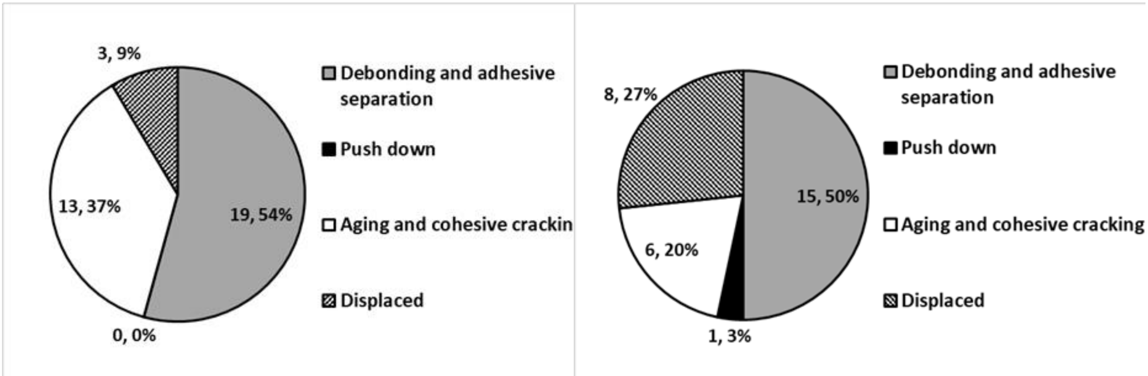


(b) Moisture existence

Figure 3.7. Inspection method for sawcut cleanliness (multiple selections) and moisture.

3.3.3.3. Distress Type

The survey included questions regarding the joint sealant distress types most frequently experienced. The results are shown in Figure 3.8. Both hot-pour and silicone sealants frequently saw debonding and adhesive separation. The next most frequently occurring distress types were aging and cohesive cracking.



(a) Hot-pour sealant *(b) Silicone sealants*

Figure 3.8. The principal distress types experienced (multiple selections)

Debonding and adhesive separation mostly stem from joint preparation. Aging and cohesive cracking result from inadequate design and product selection. Therefore, further discussion is needed regarding the appropriate joint sealant conformational design. Such an analysis should incorporate the narrow joint width used in most states and how states can properly clean and inspect narrow reservoir widths.

3.4. Discussion

Although there is still controversy over whether or not joints should be sealed, most states continue to use joint sealants. The sealing of rigid pavement prevents erosion and loss of subbase. An evaluation of erosion potential is key to ensuring good sealant practices and high pavement performance [50]. The life span of the concrete pavement is extended through a reduction in the amount of water that penetrates the pavement and causes water-related problems, if the joint sealant is not destroyed early on and performance is maintained for a long period of time. Therefore, proper assessment of erosion potential is key to effective sealant practices and high pavement performance.

In the joint reservoir designs analyzed for this research, joint width tended to be narrower than the design guidance of the ACPA. The use of very narrow joints presents serious challenges to both joint preparation and sealing operations; neither can be carried out with any degree of confidence. Obtaining the required cleanliness in a narrow joint is much more difficult than in other configurations. These factors, in combination with higher stress levels, all but assure early debonding and sealant failure.

Some DOT practices do not fully adhere to established guidance with regards to SF limits. In addition to this trend, it may be necessary to reconsider the sealant thickness under the SF values proposed by the ACPA, because joint width now tends to be very narrow, making it difficult to ensure adequate durability. As reported in a number of previous studies, narrow and deep joint sealant configurations tend to increase stress levels, as compared to conventional joint configurations (SF $\geq$ 1, square or wide rectangle) at the same degree of deformation.

Silicone sealants are recommended by the ACPA for recessed configurations, while hot-pour sealants are recommended for flush-filled configurations. However, surprisingly, more than half of the hot-pour sealant-using regions were found to use the flush-filled configuration, not following conventional guidelines. The flush-filled configuration is recommended for hot-pour sealants because it eliminates non-compressible storage space and maintains more ductility, due to being kneaded by tires passing over the sealant [34]. Therefore, further investigation is needed regarding why agencies are employing this surface configuration and providing an evaluation of its performance.

There was no trend found in the way institutions arranged joints when installing sealants. Joint preparations were carried out in accordance with the methods and procedures of the particular agency. Some states delegated joint preparation to the installation contractor. In addition, agencies seemed to need additional support for current inspection and assessment methods, which ideally would be a process that could be carried out before sealant installation. Otherwise, agencies have little choice regarding when and how to inspect sealant installation work and no means of alleviating quality-related problems that they may experience.

One key conclusion from examining the data obtained from the survey is there is a lack of documented joint sealant condition data. Many DOTs understand that a critical element of concrete pavement performance is the joint sealant, but when considered as a key item for ensuring the life of the pavement, it appears that the joint sealant is less emphasized. Joint sealants are considered an unnecessary expense that can be ignored if there are no improvements seen in long-term pavement performance and verification. Thus, documentation and standardization of design, joint preparation, and performance from a long-term perspective are required.

3.5. Closing Remarks

This research examined the effects of moisture content on the bond strength between a joint sealant and concrete pavement. Based on the results presented here, the following conclusions were drawn:

- Of the 50 states in the United States, 41 (82%) responded to a joint sealant practice questionnaire. In response to questions about seals and no seals, most states reported using joint sealants.
- According to the results of the joint sealant survey, many states used joints narrower than the conventional joint widths. The configuration and design criteria of the sealant according to this narrower joint width appear to conflict with established recommendations from the ACPA.
- Regarding the surface configuration of joint sealants, most states responded by using silicone and hot-pour sealants with recessed surface treatments. In particular, hot-pour sealant use appears to be at odds with the ACPA's recommendations, requiring further investigation of reasons supporting this practice and its effect on performance.
- For most agencies, preparation of the joint is visually inspected. In addition, agencies appear to lack the tools and control protocols needed to facilitate proper inspection of cleaning and joint preparation work.
- The premature failure of debonding was the principal distress type referenced in the survey responses. Early-stage failure stems from improper or insufficient joint preparation and design rather than the material itself. Therefore, DOTs should reconsider their design and joint preparation for narrower joint widths.

4. EFFECTS OF SHAPE AND BOND STRENGTH ON ADHESIVE FAILURE OF JOINT SEALANTS

4.1. Section Summary

The current joint sealant is designed without consideration of bond strength between concrete and sealant and the effect of shape on stress concentration. This often leads to adhesive failures within 1.5 years, earlier than the expected service life of the joint sealant, 20 years. In adhesive failure, the strength of the bond and the stress of the interface between the sealant and the face of the joint reservoir play a very important role. Therefore, to examine the nature of the bond along the sealant/joint reservoir interface, experimental bond tests are conducted. In addition, the stress distribution on the interface is also investigated according to geometry (Shape Factor (SF) and Degree of Curvature (DoC)). Re-evaluation of the SF was conducted, and a new design factor, DoC, was introduced and investigated through the Finite Element Method (FEM) of analysis. With these factors, the reduction of bond strength and increase in the stress at the interface can be limited reducing the potential for early adhesive failure. Based on this study, the effect of joint preparation (dirt and moisture) on joint strength and shape (SF and DoC) of joint sealant should be considered when designing and installing sealants.

4.2. Introduction

Concrete slab construction involves sawing joints to control climatically induced cracking and a sealing operation to place a sealant material in a rectangular-like configuration

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within a joint reservoir. Achieving long-term performance of concrete pavement is one of the key challenges facing the concrete highway industry today, and joint sealants is an important part of meeting that challenge [2, 3, 37]. Sealant failure, commonly associated with the infiltration of moisture into the base, in a rigid pavement is a major cause of loss of load carrying capacity and shortening of pavement service life [36]. Therefore, maintaining the life span and functionality of the joint sealant is important for the life of a concrete pavement.

With respect to the level of performance, a joint sealant is expected to mainly adhere to two types of failure mechanism; cohesive and adhesive failure [5]. Both cohesive and adhesive failure may have a severe effect on the performance of a sealant [27]. Cohesive failure typically does not occur until several years after placement, but it is defined as the failure that occurs within the material itself when stress levels exceed the strength of sealant. These stresses are often caused by several factors such as joint movements and traffic loading. Adhesive failure is defined as a failure at the sealant-joint reservoir interface. Adhesive failure (i.e., debonding) is the most common failure of joint sealant. It often occurs early ages, as early as 1.5 years, after installation and therefore is also referred to as a premature failure [39, 51]. The failure often caused by stress concentration at interface and/or improper joint preparation. [5, 6, 39].

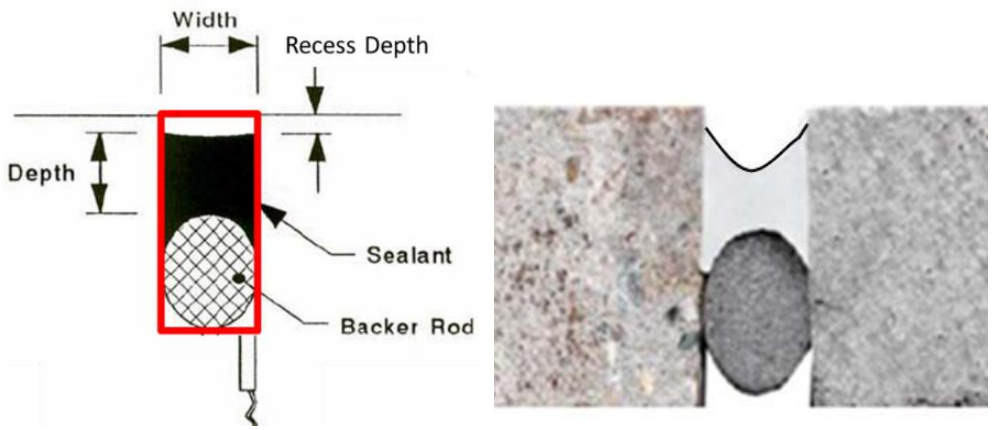
The bonding and the shape of the sealant within the joint reservoir should be considered as the major factors with respect to adhesive failure that affect performance in newly constructed pavements. Despite recent advancements in pavement design and construction quality control, it is doubtful that the challenges related to the proper installation and shaping of joint sealants have been completely resolved at least for adhesive failure. Therefore, this study investigates the stress distribution depending on geometry and bonding behavior according to joint preparation to minimize the incidence of premature failure.

4.3. Current Geometric Considerations

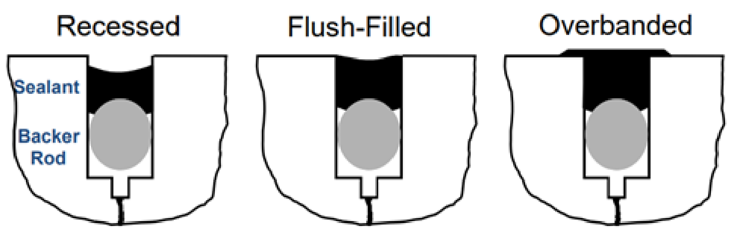
Recent design protocols for joint seals typically address certain geometric factors to limit stress levels. To investigate the effects of these factors on joint sealant behavior, background information detailing the effect of joint sealant configuration and the associated limits is addressed.

4.3.1. Joint sealant configuration

The joint sealant system consists of the joint sealant, the backer rod, and the joint reservoir or reservoir as shown in Figure 4.1(a). There are three types of joint sealant material; silicone, hot-pour, and compression seal. Backer rods are used to control the composition and shape of the sealant as well as to prevent bonding to the bottom of the joint reservoir. The reservoir has three main dimensions; joint width, depth, recess depth. The reservoir size should be selected to accommodate the movement of pavement to maintain strain levels to certain limits. Reservoir size is also an important factor to facilitate the proper cleaning prior to installation of a sealant. The joint width (min. ¼ in.) is determined by the length of the concrete slab and the climate zone. The depth (min. ¼ in.) can be determined by adhering to selected shape factors (min 1/1 to max 2/1) which is depth over width. Recess depth (1/4 to 3/8 in.) exists to prevent direct contact with a passing tire and to limit tire noise [2].



(a) Typical configuration of joint sealant



(b) Noise reduction design

Figure 4.1 Joint sealant configurations [2, 3, 5].

As shown in the Figure 4.1(b), the configuration of the joint sealant can be varied (recessed, flush-filled, or over-banded), depending on the degree of noise reduction [3]. However, without a mechanical interpretation of the joint configuration, the size or shape of the sealant may not be optimally determined which likely leads to adhesive failure.

4.3.2. Maximum Allowable Strain Limitation

One factor that has been considered for several years in joint seal design is a suitable limiting strain level that would deter premature sealant failure. Tons [26] based his considerations on the empirical analysis suggesting that the maximum limit for a sealant need to be set at 20 percent. It was based on the parabolic behavior of the sealant cross section under displacement with the assumption the strains in the sealant are uniformly distributed along the outer parabolic lines within the sealant. His suggestions have been widely used and taken into consideration by many sealant investigators. Bugler·[52] also recommended a 20 percent limit of the strains to design a sealant cross section. Chong and Phang [53] and Anderson et al. [54] suggested that the maximum allowable sealant tensile strain should be 20 to 30 percent. Currently, the maximum allowable strain of 20 percent is still the most agreed upon number used by sealant investigators to design a sealant configuration.

4.3.3. Design Considerations of Behavior

Sealants are usually placed in warm weather, when the joint reservoir is at its minimum width. As a result, the sealant tends to remain in tension throughout its service life. If the sealant is placed in cold weather when the joint is at its maximum width, the sealant would remain in compression throughout its life. Alternatively, if a joint is sealed in a moderate weather condition, when the. joint width is somewhere between the narrow summer and the wide winter widths, the seal will be subjected to both tensile and compressive movements [27, 28]. Tons [55, 56] proposed an approach for the measurements of horizontal joint movements that uses a modified thermal coefficient of expansion (or contraction) and an estimated coefficient of variation.

For design purpose, extrusion (or bulge) and intrusion (or sag) of the concrete joint sealant is another consideration. Extrusion and intrusion of the sealant material are known behavior patterns that are a function of the sealant elastic properties and the geometry of the joint reservoir in addition to the temperature conditions at the time of placement [57].

Both sealant bulge and sag are important in certain states that would need to be considered along with any limits on tensile strain to minimize debonding.

To understand the actual behavior of a joint sealant, it is first necessary to develop a material model or a constitutive equation which reliably describe the relationship between stress, strain and stiffness. Although the SF in long-term observations is an important factor to improve sustainability, there have been not many related follow-on studies since the research by Tons [26]. Moreover, several new sealant types have been introduced, and thus additional research on shape factors may be required. Research on the widening of the joint reservoir and reconfiguration of the sealant SF due to the effects of sealant rehabilitation as well as aging is also required.

4.4. Finite Element Analysis

The shape of a sealant affects the magnitude of stress at the bonded interface as well as within the body of the sealant. Several sealant types have been improved and introduced over the years, but there is a lack of information about the effect of the shape on their behavior. It is important to improve and understand the effects of stress concentration depending on shape for understanding behavior of sealants to maximize their life and the life of the pavement. Therefore, in this study, these effects are examined using finite element methods (FEM) according to the shape factor (SF). A new design factor, degree of curvature (DoC), is also introduced since it pertains to the stress on the bonded surfaces.

4.4.1. Limiting Shape Factor

The SF, first defined by Tons in 1959, is the ratio of the depth (D) to width (W) of the sealant as shown in Figure 4.2. The joint reservoir width and insertion depth of the backer rod define the sealant shape. The SF is critical to the long-term success of poured sealants. SF is generally recommended as 2.0 for silicone and 1.0 for hot-pour material [2]. Today, however, the joint width is limited to reduce road noise (to 3/8 in.) and to a thickness of 1/4 in. to ensure constructability, making it difficult to simply apply [58]. Meeting these criteria yields a SF = 1.5.

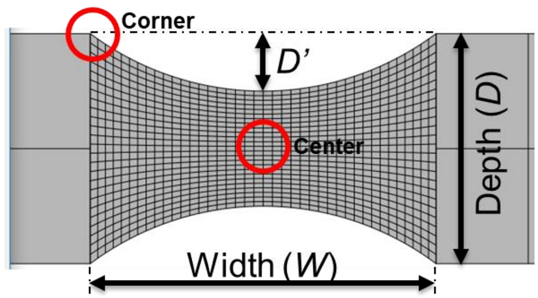


Figure 4.2 Shaper factor and Degree of Curvature Schematic (eg. SF 1.5 and DoC 0.3)

4.4.2. Degree of Curvature (DoC)

Tons [26, 29] recommended to use an hourglass section for the sealant configuration as shown in Figure 4.2. However, the criteria associated with an hourglass shape has been somewhat ambiguous and is often ignored in construction. Analysis, subsequently presented, illustrates the advantages that the hourglass shape yields in reducing stress concentration at the sealant edges and corners. To facilitate investigation of the effects of an hourglass shape, the parameter, Degree of Curvature (DoC) is introduced and defined by

$$DoC = 2 \times \frac{D'}{W} \times SF = 2\frac{D'}{D} \tag{4.1}$$

where *D'*= Sealant center thickness; *W* = Sealant width; *SF*= Shape factor = $\frac{W}{D'}$; and *D* = Sealant edge thickness.

Since a joint sealant system typically includes a backer rod, the resulting curve at the bottom of the sealant is essential and its effect is also important to consider. To this end, FEM analysis was carried out over a range of DoC values (from 0 to 1) to compare the stresses with those of a rectangular section.

4.4.3. Finite Element Modeling (FEM) and Analysis

For the FEM analysis, the sealant material was assumed to be an incompressible similar to rubber (i.e. Poisson's ratio 0.5). The element boundaries were assumed to be free at the bottom and top of the sealant and a perfectly bonded between the walls of the joint reservoir and sealant. These conditions were accommodated using a node bilinear plan element (CPS4R) for the analysis. The finite element modeling was based on a 25- x 38- element model. Figure 4.3 shows the FEM model and the boundary conditions used.

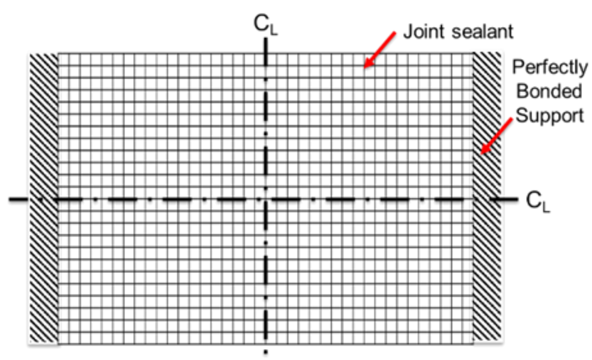


Figure 4.3 FEM modeling and the boundary conditions

External stimuli in the analysis applied in a horizontal direction from the bonded plane. The overall strain of the sealant was evaluated through its displacement. Stress was evaluated in the corner and center as shown in Figure 4.2, respectively.

Elastic response of rubber-like materials is often modeled based on the Mooney–Rivlin model which can be expressed by [28, 36, 59]:

$$\mathrm{U} = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \tag{4.2}$$

where C_{10} and C_{01} = empirically determined material constants; I_1, *and* I_2 = the first and second deviatoric strain invariants [60]. The constants C10 and C01 are determined by fitting the predicted stress from the above equations to the experimental data. The recommended tests are uniaxial tension, biaxial compression, biaxial tension, uniaxial compression, and for shear, planar tension and planar compression [27, 61].

To determine C10 and C01 constants, in this study, the uniaxial tensile tests (ASTM D412) were carried out at a uniform rate of displacement of 500 mm/min using a silicone sealant (DOW 888). The shape and dimensions of the die for preparing the dumbbell specimens is shown in Figure 4.4 [62]. Based on the tensile test data, the constants C_{10} and C_{01} are determined to curve fit the measured data to back out the coefficients as 0.1065 psi and 20.0524 psi, respectively, for the used silicone sealant. The predicted hyper-elastic model (Mooney-Rivlin) in the seal cross section with the constants and the test data is shown in Figure 4.5. The elastic behavior is the basis of this study since it focuses on stress distribution according to cross-section rather than material properties.

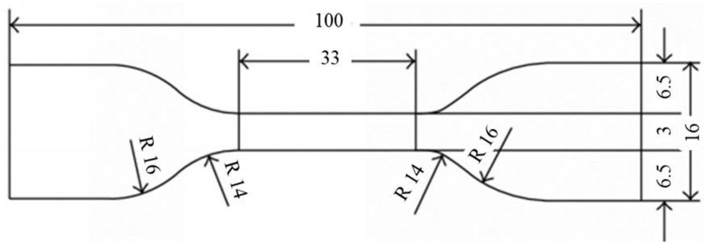


Figure 4.4 Tensile test specimen dimensions

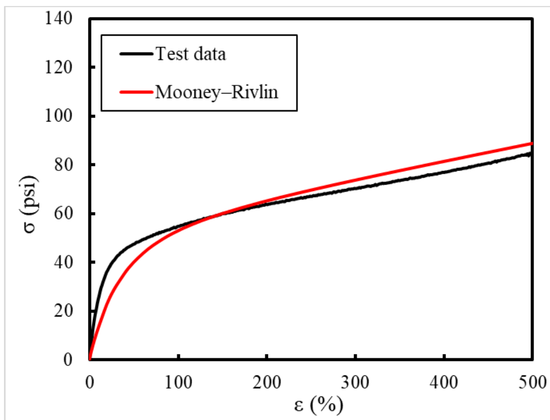


Figure 4.5 Experimental data for simple extension and Mooney-Rivlin model

The Equivalent Von Mises stress was used to show the values of the stress and strain analysis results. Because the Von Mises stress takes the form of a scalar without direction, it is very convenient to estimate stress by a single parameter without considering directions of stress. Equivalent Von Mises stress and maximum displacement were calculated in accordance with different SF and DoC. The FEM analysis was conducted up to a strain level of 30 percent since the strain more than 30 percent exceeds the fatigue limit of the material [28].

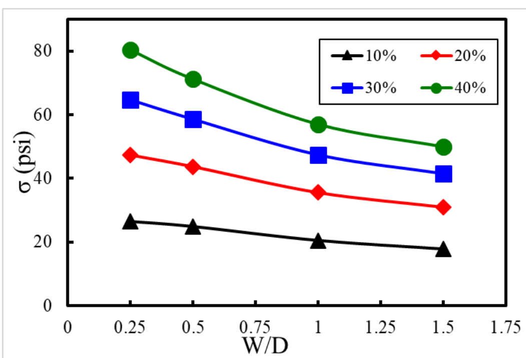
First, rectangular sealant cross sections were analyzed to investigate the effect of SF. The width (*W*) was kept constant at 0.375 in., and the depth *(D)* was varied with values as follows: 0.25, 0.375, 0.75, and 1.50 in. For DoC, the width (*W*) was kept constant at

0.375 in., and the depth of the center (*D'*) was varied with values as 0.01875, 0375, and 0.05625in.

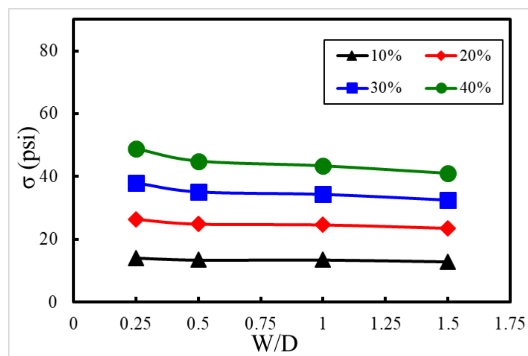
Under tensile strain, results for Von Mises stresses were dependent upon the SF as shown in Figure 4.6. The stresses under an opening displacement were extracted from the center and corners. Displacement values are normalized to the width of the sealant allowing the displacement to be determined by multiplying the width by SF.

4.4.3.1. Effects of Shape Factor changes

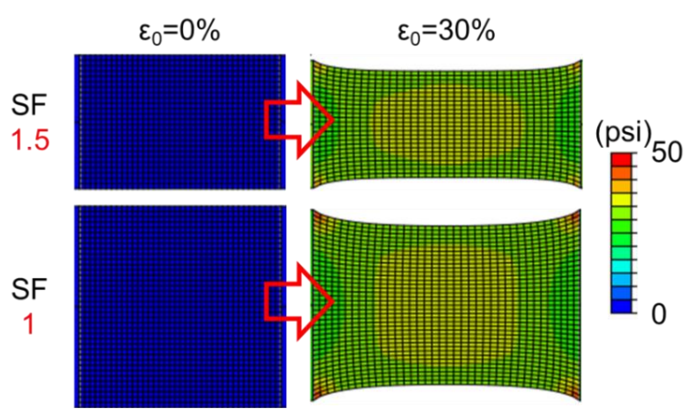
As shown in Figure 4.6(a) and (b), stress increases in the center and corners of the sealant as W/D increases.



(a) Equivalent Von Mises stress at corner versus W/D in tensile displacement



(b) Equivalent Von Mises stress at center versus W/D in tensile displacement



(c) Equivalent Von Mises stress distribution with SF 1.5 and 1.0

Figure 4.6 Stress Analysis Results by SF.

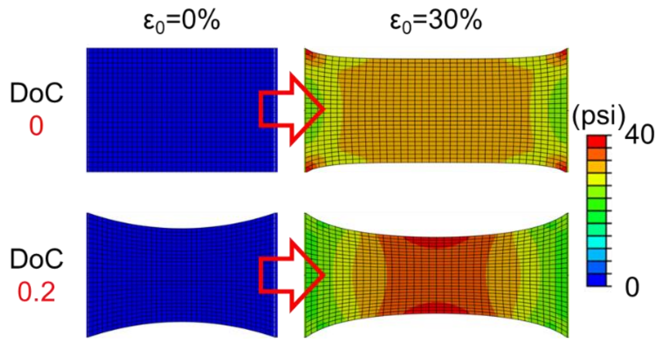
If the width is fixed, the stress increases as the depth of the sealant increases. Changes in stress due to an increase in *W/D* and strain levels vary similarly as noted in Khuri's study [28]. In addition, for the stress distribution of rectangular sections, the stress of the edges at the same 30 percent strain is greater at the center (Figure 4.6(c)). In this study, the stress at the bonded interface can be reduced as the thickness of the sealant is reduced.

4.4.3.2. Effects of Degree of Curvature: Symmetrical section

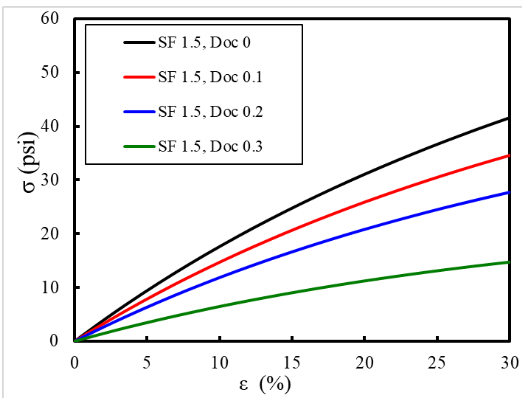
Regardless of the stress distribution (Figure 4.7(a)) according to DoC, the maximum stress of 40 psi occurs when the analysis result is a strain of 30 percent. However, the position of maximum stress occurs at the corner, and DoC = 0.2 occurs in the center. As shown in Figure 4.7(b), as DoC increases, the stress of the interface is reduced. Also, regardless of SF, increasing DoC also reduces corner stress as shown in Figure 4.7(c).

4.4.3.3. Effects of Degree of Curvature: Unsymmetrical section

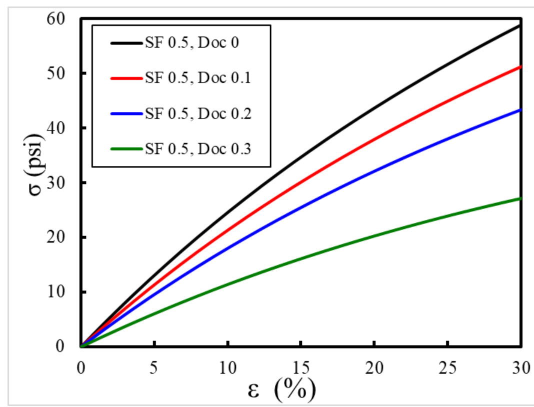
Since various sealant configurations have been proposed by ACPA to reduce road surface noise as shown in Figure 4.1(b), where the configuration of the sealant consists of a top surface with varying curvature. Figure 4.7(d) shows stress analysis results for the unsymmetrical cross-sections. Maximum stress is a similar result, but distribution of stress and stress concentration location are different. In the unsymmetrical configuration, the results are similar to those for a rectangular cross-section (Figure 4.7(e)), even if the bottom surface is recessed. Therefore, recessing the bottom (or using a backer rod) alone may not increase the life span of a joint sealant.



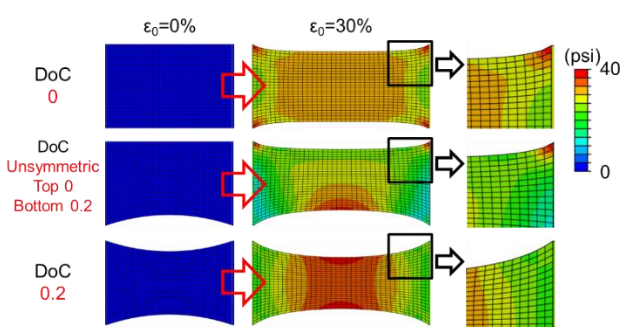
(a) Stress analysis result for changing effect of the DoC



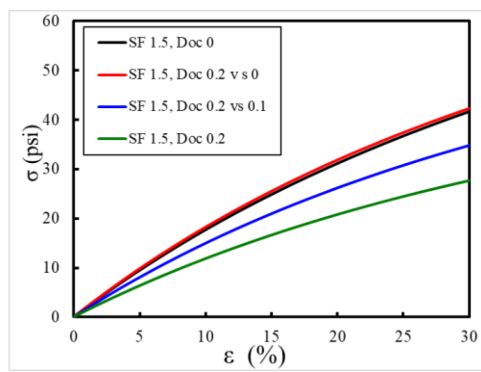
(b) Stress analysis results at corner of SF 1.5 with various DoC



(c)Stress analysis results at corner of SF 0.5 with various DoC



(d) Stress distribution on Unsymmetrical section



(e) Stress analysis results depending on shape

Figure 4.7 Results of stress analysis according to DoC in symmetrical section and unsymmetrical section

4.5. Bond strength Evaluation

Current specifications for joint sealants do not establish minimum bond strengths. However, field studies of laboratory-approved sealants that have met the specified requirements noted that premature bond failures still occurred in the field [17, 63, 64]. It is generally agreed that most early failures are caused by the adhesive problem at the interface. If the joint sealant is improperly installed, the sealant material may undergo bond failure, thus making the pavement structure susceptible to infiltration of water and a shortened service life [5, 6, 40, 65].

Very few studies have considered the effects of moisture and dirtiness on bond strength. A study on the effect of moisture on sealant bond strength was recently conducted by Qiang, et al.[66] but other studies focused much of the discussion on a difference methods to quantify the effects of moisture and dirtiness on the bonding behavior [40, 43, 67].

Bond failure may occur even if a joint sealant is geometrically configured appropriately (within appropriate SF and DoC limits). Even though elastic limits of the jointing materials are perhaps never exceeded, avoiding debonding failure is still a challenge. Figure 4.8 shows the relationship between the stress at the bond interface and the bond strength on a probabilistic basis. Both the stress and the strength have a mean and distribution associated with them depending upon geometric factors. Alternatively, when the bond strength becomes less intense or the stress of the joint interface increases, the probability of failure increases. For instance, if the joint is not appropriately cleaned during the installation, the strength may be reduced or compromised. Therefore, the effects of joint preparation on the bond strength are investigated and reported in this paper.

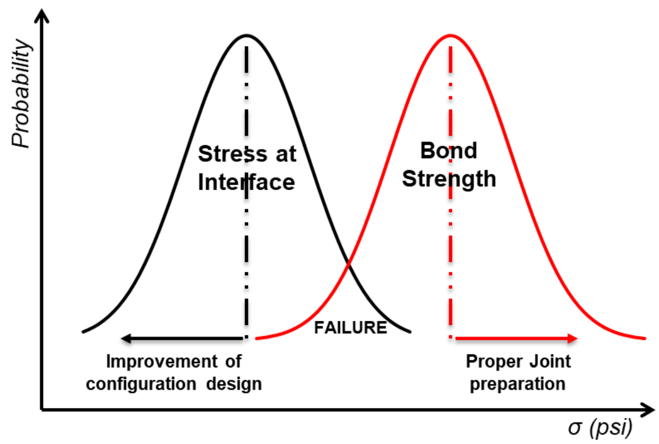
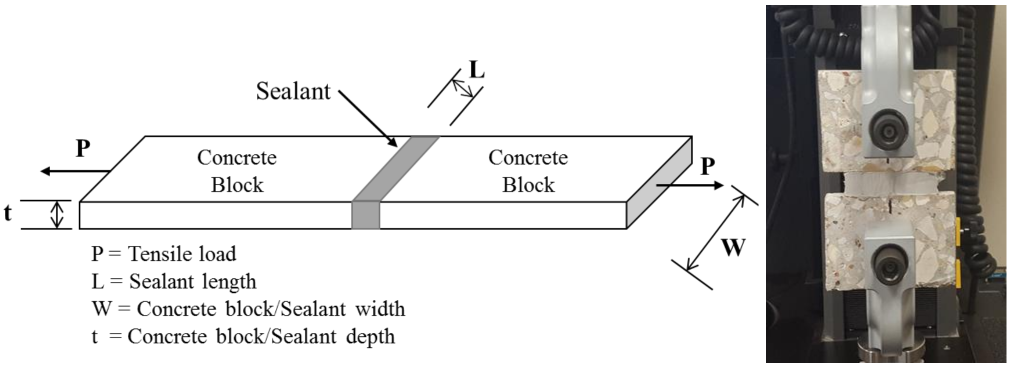


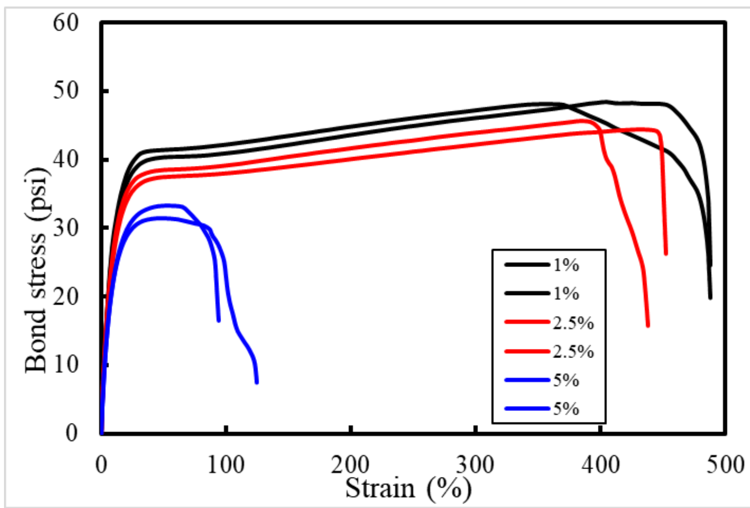
Figure 4.8 Adhesive failure probability at joint sealant.

4.5.1. Test Specimens

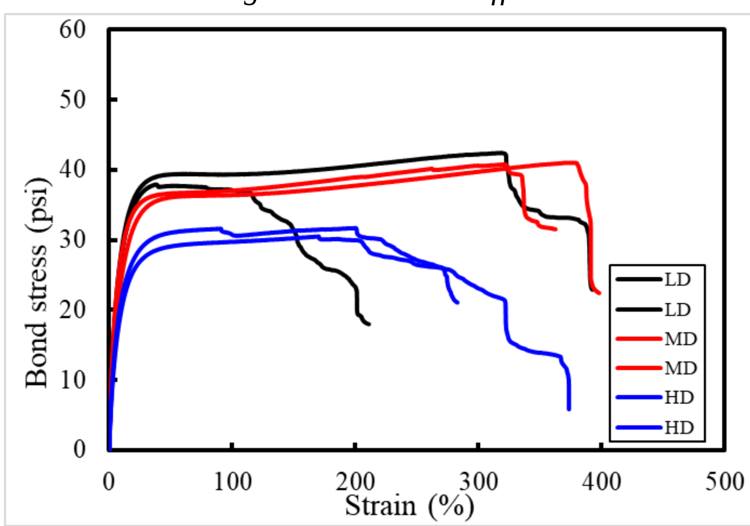
Total twelve tests were conducted to investigate the relation between the bond strength and the joint preparation for a Dow 888, Non-Sag silicone sealant. The test specimens (Figure 4.9(a)) consisted of two concrete blocks that served as the wall of the joint reservoir to provide a surface bond with the sealant. Each concrete block consisted of a depth (t) = 0.5 in. (12.7 mm), a width (W) = 3 in. (76.2 mm), and a length (L) =2 in. (50.8 mm). The sealant dimensions were t = 0.5 in. (12.7 mm), W = 3 in. (76.2 mm), and L = 0.5 in. (12.7 mm). Since the properties of silicon do not change significantly with changes in temperature [28, 68] the testing was carried out at room temperatures.



(a)Schematic view and a picture of test specimen



(b)Tensile Bond strength test result on different moisture content



(c) Tensile Bond strength test result on degree of dirtiness

Figure 4.9. Bond strength test schematic diagram and test result values.

4.5.1.1. Moisture content

Moisture test specimens were prepared for three different moisture levels. The moisture content of the concrete blocks was varied to achieve different moisture contents prepared follows: 1) oven dry to 0 per water content; 2) place into water (different moisture level in each block); and 3) dry at room temperature followed by measurement of the weight of the block to obtain water content. The moisture level was categorized into the levels of high (HL, wet), medium (ML, the surface is dry, but there is moisture inside), and low (LL, dry), which represented the water contents of 5, 2.5, and 1 percent, respectively. Levels of moisture content was obtained by

$$MC = W_w / W_{conc} \tag{4.3}$$

where MC = moisture content; W_w = weight of water; and W_{conc} = weight of concrete block at oven dry condition.

The concrete blocks at specific water content levels were wiped with a clean, dry, lint-free cloth prior to place the sealant.

4.5.1.2. Degree of dirtiness

The concrete blocks were prepared to achieve three different degrees of dirtiness: 1) clean the concrete block by clean, dry, and lint-free cloth (low dust, LD); 2) A gram of dust has been applied to the surface (medium dust, MD), assumed to be similar to a cleaned sawcut surface prior to installation; and 3) intentionally adding 3 grams of mud to the surface (high dust, HD). The degree of dirtiness was categorized into the levels of high (HD), medium (MD), and low (LD), which represented the degree of dirtiness of 0 oz/in^2, 0.0235 oz/in^2, and 0.071 oz/in^2, respectively. Degree of dirtiness was obtained by

$$DD = W_D/A_{conc} \tag{4.4}$$

where DD = Degree of Dirtiness; W_D = weight of dirtiness; and A_{conc} = Interface Area of concrete block.

4.5.2. Bond Strength Test

An Instron tensile tester (Model 5943) was used for the sealant bond testing. The test specimen was placed in the grips of the testing machine, using care to adjust the specimen symmetrically to distribute tension uniformly over the sealant cross-section. The specimens were pulled at a constant crosshead velocity of 0.33 inches/s until a failure occurred. “Failure” refers either to a tearing apart of the sealant material (cohesive failure) or a detachment of the seal from the concrete block substrate (adhesive failure)[66]. The true stress and strain developed in the sealant material was calculated using the mathematical expressions of

$$\sigma_t = \sigma_e(1 + \varepsilon_e) = \frac{P}{A_0}(1 + \frac{\Delta L}{L_0}) \tag{4.5}$$

$$\varepsilon_t = \ln\left(\frac{L_i}{L_0}\right) = \ln\,(L_i + \frac{\Delta L}{L_0}) \tag{4.6}$$

where σ_t = the true stress; σ_e = engineering stress (nominal); P = applied tensile force; A_0 = the initial area of the test; ε_e = the engineering strain; ε_t = the true strain; L_0 = initial strength; L_i = instantaneous length; and ΔL = change in length.

Stress-strain results from laboratory bond testing at three different moisture contents (*MC*) are shown in Figure 4.9 (b). The nominal ultimate stress for the sealant varied from 31 to 50 psi (0.2 to 0.3 MPa). The stress-strain curves were similar amongst all the specimen but showed a significant difference in the magnitude of the tensile stress with respect to moisture content. An adhesive failure was observed from all specimens.

Increasing moisture content after a certain point (2.5 percent) resulted in substantial decreases in the bond strength of silicone sealants. Based on the test results, the low level (48 psi, 1 percent) specimens had 1.45 times greater average bond strength than high level (33 psi, 5 percent) specimens. In addition, the moisture content of 1 to 2.5 percent shows a rupture strain of 400 to 500 percent. However, a only100 percent strain appears in high moisture content.

Figure 4.9(c) shows the stress-strain behavior of the specimens under three different dirtiness level (or cleanliness level). The low-level specimens (42 psi) had 1.31 times greater average bond strength than high level specimens (32 psi). High degree of dirtiness has a value of 32 psi bond stress at 30 percent strain, the initial modulus and ultimate bond strength are significantly reduced. In addition, the rupture strain varies depending on the moisture content, whereas the strain does not vary much depending on the dirtiness.

4.6. Discussion

The study was conducted to investigate design measures to reduce early adhesive failure and to maintain the life span of the sealant. Analysis of the rectangular shape sealant behavior showed that as SF, a major component in the design of sealant, increases, the magnitude of stress was reduced. However, at 30 percent strain, stress concentration was observed at the corner (the interface between concrete and sealant). Increasing SF is one way to prevent adhesive failure by reducing stress but there is still a limit to eliminate stress concentration at the interface corner only with SF. Since the coupling of silicon polymer is much stronger than coupling of the polymer and concrete, creating a stress concentration in the more interior regions of the sealant (center) is another way to reduce adhesive failure. To further characterize the stress concentration in the sealant, in this study, DoC was proposed. By increasing DoC, the stress concentration at corner was eliminated and the maximum stress appeared in the center of the section based on the analysis. The most desirable sections are the thin sections and symmetrical curved sections that can reduce the amount of maximum stress and eliminate the stress concentration of the interface between concrete and sealant.

Although a sealant is designed adequately, the adhesive failure may occur if the bond strength is lower than the stress of the interface due to improper joint preparation. Therefore, this study investigated two factors (moisture and dirtiness) in joint preparation that could affect the bond strength. It shows that a certain level (or higher) of moisture content and dirtiness on concrete surface significantly decrease the bond strength. It is suggested that consideration of DoC, SF, and joint preparation as all important factors to prevent adhesive failure and to maintain the sealant's lifespan.

4.7. Closing Remarks

The effect of the shape of the sealant on the resulting stress levels in a joint sealant and the variation in bond strength as to moisture and dirtiness effects were investigated towards the introduction of a new parameter called the degree of curvature (DoC). The FEM method of analysis used to assess stress levels incorporated the use of the incompressible hyper-elastic model (Mooney-Rivlin) and the results of laboratory measurements from the comparison of different sealant cross sections. The analysis was used to calculate deformation and displacement using specific assumptions. Comparisons between all sections were performed on the basis of changes in depth, SF, and DoC. Based on the research present herein, the following conclusions may be drawn:

- To prevent adhesive failure in early age, SF and DoC of the joint sealant need to be increased to reduce stress throughout the section and to eliminate the stress concentration at the interface between sealant and concrete. Recession of the sealant at the top surface will not offset the effects of not including a backer rod in the joint reservoir.
- Unsymmetrical sections currently used in the field to reduce road surface noise shows a stress concentration similar to a rectangular section. Therefore, hourglass shape section is recommended as Tons [26] originally proposed.
- Both moisture and dirtiness on the interface between concrete and sealant significantly decrease the bond strength. It may require adequate joint preparation and need criteria to standardize.
- The proper design and construction of joint sealant may reduce the early adhesive failure and maintain (or improve) the service life of the sealant and concrete pavement.

5. INVESTIGATION AND EVALUATION FOR THE DESIGN AND BEHAVIOR OF CONCRETE PAVEMENT JOINT SEALANTS

5.1. Section Summary

Joints in concrete pavement are intended to provide freedom of movement in a concrete slab relative to the volumetric effects. Changes such as this can occur due to drying shrinkage, temperature changes, and moisture differences that develop within the slab. A key reason to seal rigid pavement joints is to prevent or at least reduce the amount of water from rainfall events infiltrating the pavement structure, which can ultimately contribute to subbase erosion, loss of support, and the build-up of fine, incompressible material on the face of the joint. The strength of the joint sealant bond and stress of the interface between the sealant and face of the joint reservoir play important roles in joint sealant failure. Thus, in this research, experimental coupling tests were conducted to investigate the geometric characteristics of sealant/joint reservoir design. The stress-strain relationship on the interface was investigated according to its geometry, both in terms of the shape factor (SF) and degree of curvature (DoC). The SF and DoC were evaluated through a tensile test of the joint sealant based on these geometric characteristics. Also discussed are the SF of the joint sealant currently being recommended, SF most appropriate for a narrow-width joint, and surface finish of joint sealant. Based on this study, the effects of sealant geometries (i.e., SF and DoC) should be considered during design and installation. Also, further

*Reprinted with permission from "Experimental Study on the Design and Behavior of Concrete Pavement Joint Sealants" by Jinho Kim, Dan Zollinger, and Seunghyun Lee, 2021. *Transportation Research Record*, DOI: 10.1177/0361198121993472, Copyright 2021 by Jinho Kim Dan Zollinger, and Seunghyun Lee research on more realistic SFs for narrow-width joints and self-leveling sealants is recommended.

5.2. Introduction

Joints in concrete pavement are needed to provide freedom of movement at the joints due mainly to the effects of external changes in the environment during and after placement of the concrete. Functionally speaking, joints are designed to control cracking, minimize stress in the pavement caused by these external effects, and prevent damage due to immovable objects adjacent to the pavement.

The basis for joint sealant geometry and design was established many years ago [69]. The practice of placing joints at regular intervals has been validated by years of experience. The first specifications regarding joint sealant placement in concrete pavement were included in guidelines for transverse joint spacing created by the American Concrete Institute in 1914 [11]. Discontinuities in Portland Cement Concrete (PCC) pavement [12] (such as joints) continue to be a major performance concern because they tend to create planes of weakness in the slab; in many instances, distress often initiates and propagates at or near joint locations. Therefore, attempts have been made to reduce the number of joints by extending joint spacing, but such measures tend to be offset by the effect of the thermal coefficient of expansion associated with slab movements that are manifest at a joint. Customized curing techniques and construction methods have had some success in yielding PCC pavement with longer joint spacing, and field observations related to the improvement of joint patterns has offered suggestions for avoiding early distress at joints [13].

5.3. The Role of Joint Sealant in Infiltration Diversion

Analysis of the Federal Highway Administration's Long-Term Pavement Performance data has revealed that a pavement's foundation (subgrade and/or subbase) is one of the most critical design factors in achieving excellent performance [70]. For pavement designers, one of the most important elements in optimizing their designs is the assumption that the use of joint sealants will protect the supporting layers from water infiltration during rainfall events. Pavement mechanistic-empirical (ME) software that recognizes the need for proper functioning of joint sealant systems in this manner by including an input for this factor. It is these types of consideration that are necessary for ascertaining whether and what type of sealant to use for a given project.

Because of its rigidity, concrete pavement has a high degree of load-spreading capacity that typically results in low sublayer stresses and the potential for concrete pavement slabs to be placed directly on a compacted natural subgrade. However, it has long been known that an adequate subgrade is essential to good concrete pavement performance. In order to ensure that adequate subgrade support is present, joint sealing must be coordinated with improved subgrade stabilization or the inclusion of an additional sublayer. Supporting layers must provide a stable construction platform, uniform slab support, and the necessary erosion resistance.

Sublayer erosion can lead to faulting and ultimately longitudinal slab cracking, and thus is another key factor to consider with regards to joint sealing. Unfortunately, few tools are presently available to assist with such considerations. The main elements of erosion are the effectiveness of the joint seal, rate of erosion of the subbase or subgrade material, existence of moisture under the slab, and traffic load (see Figure 5.1) [4]. Therefore, erosion is clearly linked to drainage and the effectiveness of the joint seal that limits water infiltration.

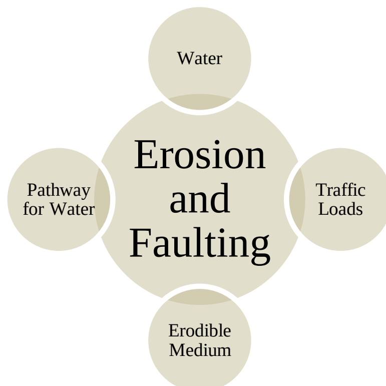


Figure 5.1. Main elements contributing to subbase erosion and PCC faulting.

When combined with traffic, erosion potential and the accumulation of water along the slab/subbase interface can often initiate pumping, transporting of eroded material, and the eventual faulting of the joint. Pumping involves the transportation of abraded and loosened material from beneath a slab, typically voiding the slab support in the vicinity of a joint. Erosion of the slab support can often lead to high deflection and possibly other types of distress that shorten the life of the pavement [11, 70, 71]. Infiltration of moisture into a pavement joint may also increase the potential for pavement blowup distress.

Sealed joints reduce the infiltration of larger-size incompressible material (i.e., sand and small stones, debris) into the joints, possibly reducing the possibility of joint distresses such as spalling due to the pressure in the joint reservoir under the load [2, 4, 37]. However, incompressible material consisting of layer upon layer of fine dirt that accumulates over time on the face of the joint is more likely to be associated with pavement blowup distress. If the slabs are unable to expand because of temperature changes, then the possibly spall damage as part of the blow-up process is a more likely temperature related possibility [72].

5.4. Joint and Reservoir Design

Joints are normally created by sawing, followed by sealing (installed with a backer rod to give the sealant the proper shape in the joint) or filling (installed without a backer rod and usually sealed full depth of the joint or sawcut) to limit the infiltration of water into the sawcut and underlying pavement substructure. Joint seals can also limit the infiltration of incompressible materials into the joint system. Unless otherwise noted, the present discussion of sealing practices collectively considers various concrete pavement joints. The key point associated with joint sealing illustrated in cross-section in Figure 5.2 [2] are the sealant (i.e., joint material) and reservoir (i.e., the cavity within the joint that contains the sealant). A backer rod (i.e., a compressible material that fits into the joint reservoir) can be employed to help establish a suitable sealant shape factor (SF) (i.e., the ratio of the sealant depth to width); this helps minimize stresses on the sealant and prevents three-sided adhesion.

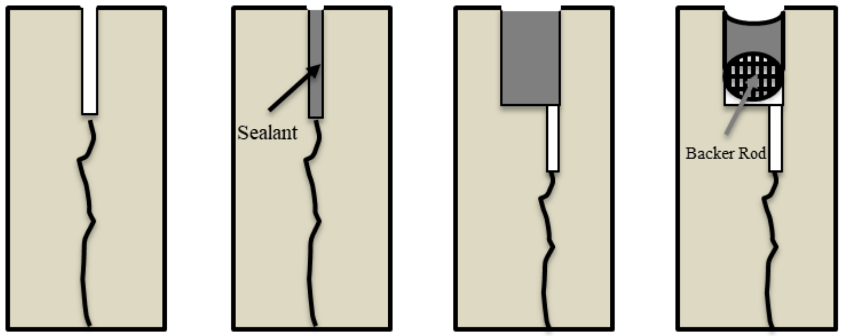


Figure 5.2. Examples of formed-in-place seals and joint filler.

5.4.1. Reservoir Size and Joint Movement

Reservoir size is an important consideration to facilitate the proper installation of sealants and ensure that joint sealants function properly. The width of the reservoir should be wide enough to enable proper cleaning of the sawcut surface to enhance adhesion of the sealant [2, 3]. A sealant must be capable of accommodating the anticipated joint opening and closing in response to temperature changes. Joint movement estimates are determined by

$$\Delta L = C \cdot L(\alpha \Delta T + \varepsilon) \tag{5.1}$$

where ΔL = expected change in slab length; in. (mm); C = base/slab frictional restraint factor (0.65 for stabilized material, 0.80 for granular material); L = slab length; in. (mm); α = PCC coefficient of thermal expansion; $\times 10^{-6}$/°F ($\times 10^{-6}$/°C); ΔT = maximum temperature range; °F(°C); ε = shrinkage coefficient of the concrete; in./in. (mm/mm) [73].

Because the width of the joint sealant varies according to the induced temperature movement, a suitable reservoir size should be selected to restrict joint movements to stay within the allowable sealant strain limits. Material and climate variability should be accounted for to avoid overextension and damage of the sealant. Variability can be addressed using probabilistic methods to encompass the range of movement for a given number of joint openings in a length of concrete pavement [74].

5.4.2. Maximum Allowable Strain

Different sealant types can withstand different levels of strain. The maximum allowable strain for a sealant depends on the amount of sealant elongation (or joint opening) and SF (see Figure 5.3) [52]. Most hot-pour liquids can withstand about 20% strain with respect to their original width. Silicone and other low-modulus materials can theoretically undergo up to 700% strain. Rubber-like materials generally do not yield, due to their hyper-elastic behavior as shown in Figure 5.4 (i.e., an immediate elastic response up to substantial strains) [28]. However, manufacturers recommend using total strains of no more than 50%, and ideally only 25% [3] in order to limit the debonding potential.

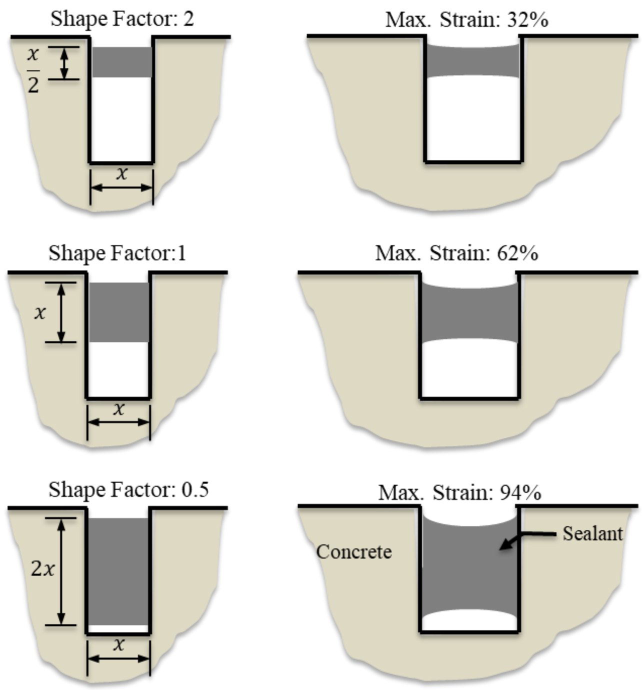


Figure 5.3. Horizontal strain on extreme sealants for different SFs.

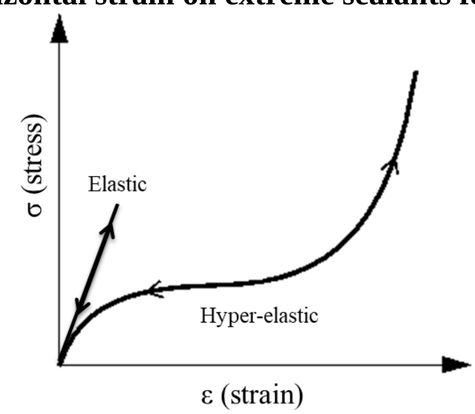


Figure 5.4. Elastic and hyper-elastic behavior.

Previous studies of stress and strain on sealants [27, 28, 36] have conservatively limited the stress levels of joint seals at 25% to 50%. However, it appears that these limits are largely empirical and lack theoretical justification. Much of the sealant research to date has focused mainly on internal stress conditions and less on the tendency of fracturing to emerge between the sealant and wall of the joint reservoir. What is lacking is a consideration of the effects of internal stress and strain and associated boundary conditions on bond stress at the sealant-concrete interface.

5.4.3. Sealant Geometry

One reasonable engineering approach to modeling sealant behavior is to account for the effects of joint width, depth, and curvature. Tons's research [26] on cell design identified the impact of SF (defined as width/depth) on performance. This remains a significant factor in current engineering practice related to the design of joint sealants [26-29].

Catsiff et al. examined rectangular sealant joints using finite element analysis. This was the first time that the stress distribution across a joint sealant was examined. Unfortunately, the researchers did not compare their work (which used rectangular shapes) to studies analyzing hourglass shapes [30-32]. Laboratory-based static and cyclic testing of joint sealants conducted by Myers [33] illustrated the effects of joint shape on sealant performance and stress distribution within the sealant. That study included various joint shapes in the analysis; however, the research did not address the effects of an hourglass shape in the laboratory testing since the focus at the time was on fillet joints. Moreover, the cyclic testing did not produce definitive results because of the limited range of strains examined. Nonetheless, the results did show – somewhat surprisingly – that the peak stress for an hourglass joint was only about one-third that of a square joint, indicating the importance of joint shape.

A recent study found that the stress distribution of the interface should also be investigated in relation to hourglass-shaped sealant geometry (i.e., the SF) by defining the degree of curvature (DoC). After re-evaluating the SF, a new design element, DoC, was introduced and investigated through the finite element method of the analysis [7]. That study suggested that the joint sealant's SF and DoC should be increased to minimize stress throughout the section and remove stress concentrations from the sealant-concrete interface, thus preventing premature adhesive failure.

Figure 5.5 shows SFs for liquid sealants. The SF, first defined by Tons in 1959, is the ratio of the depth to the width of the sealant. The joint reservoir's width and insertion depth of the backer rod define a sealant's shape. The SF is critical to the long-term success of poured sealants. An SF equal to or greater than 1 induces lower stresses in a joint sealant than does an SF less than 1. The reduced internal stresses resulting from proper SFs minimize adhesive and cohesive losses [2].

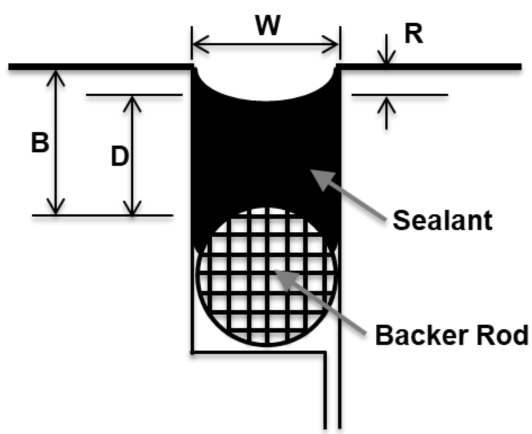


Figure 5.5. Typical reservoir configuration for liquid sealant.

Table 2.1 lists reservoir and sealant dimension recommendations for hot-pour and silicone sealants. For hot-pour materials, filling the reservoir flush with the pavement surface is preferred because experience suggests that traffic keeps the materials pliable and studies have indicated that it retains noise. For silicone sealants, SF design should include recessing the sealant from 1/4 to 3/8 in. (6 to 10 mm) to limit tire contact [58, 75].

The SF recommendation of 1 to 2 for silicone material and 1 for hot-pour sealants is based only upon material cross-sections rather than associated bond conditions [2]. The effect of using a narrow joint configuration is largely unknown. Optimizing the SF relative to the type of material and degree of bond at the sealant-joint reservoir interface should be a key item of interest. A study by the South Dakota DOT concluded that surface moisture at the interface between silicone and concrete was compounded by improper control of the installation process (i.e., a thicker cross-section). This assertion was validated through field surveys and a lab analysis of experimental data [47].

5.5. Experimental study of joint sealant geometry

The geometry of the sealant affects the amount of stress on the joined interface, as well as inside the sealant body. Several types of sealants with improvements have been introduced over the years, but information regarding the impact of shape on their behavior is lacking. In previous studies, stress strain analysis was conducted through similar tensile strength tests, but these studies focus on the effects depending on the sealant characteristics (type of sealants) on the same cross-section [76, 77]. In order to maximize the lives of both pavement and sealant, design elements related to joint sealant should be studied and improved. Thus, the influence of design elements for joint sealants was examined in this study, using experimental methods varying the SF and DoC.

5.5.1. Shape Factor

The SF is the ratio of the 'width' to the 'depth' of a sealant, as shown in Figure 5.6. The SF is critical to the long-term success of poured sealants. The recommended SF is 1 to 2 for silicone sealants and 1.0 for hot-pour materials [2]. However, the joint width is currently limited to 0.125 to 0.375 in. in order to reduce noise on the road, and to a 0.25 in. in thickness to ensure constructability [58]. When joint widths are 0.375 in. or less, the joint sealant is very thin (less than 0.25 in.), making it difficult to form a proper shape of the sealant.

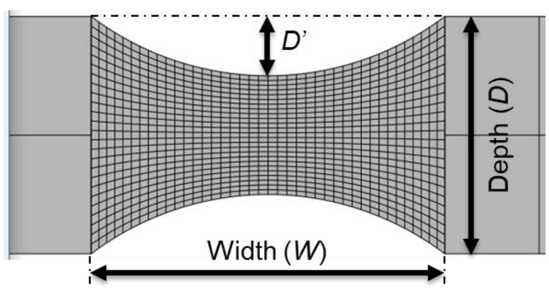


Figure 5.6. Schematic of a test specimen (ex. SF 1.5 and DoC 0.3).

5.5.2. Degree of Curvature

Tons [26, 29] recommended using an hourglass section for the sealant configuration, as shown in Figure 5.6. However, the criteria associated with an hourglass shape are somewhat ambiguous and often ignored in construction. The analysis presented below illustrates the advantages that the hourglass shape yields in terms of reducing stress concentration at the sealant edges and corners. The DoC parameter was introduced and defined with the following Eq. (4.1) to facilitate an investigation of the effects of an hourglass shape [7].

An experimental analysis was performed across a range of DoC values (0 to 0.5) to compare the stresses of rectangular sections with those of different shapes. A curve at the bottom of the sealant was found to be essential facilitated of course by the use of backer rods. Form-in-place sealants are classified either as self-leveling (SL) or non-sag (NS). SL sealants (ultra-low modulus silicone and hot-application sealants) cannot be shaped due to their low modulus, so a backer rod is inserted into the bottom and top surfaces, finishing them to a flat shape. Therefore, this study examined not only symmetrical sections but also unsymmetrical sections (with curves only at the bottom).

5.5.3. Test Conditions and Preparation

The tensile test specimen (see Figure 5.7) consisted of two concrete blocks with the sealant bonded to the walls. Concrete samples were made using the ACI mix design method with the w/c of 0.45 and the air content of 4 percent. DOWSILTM 888 (Non-sag) Silicone Joint Sealant used and typical properties are shown in Table 5.1.

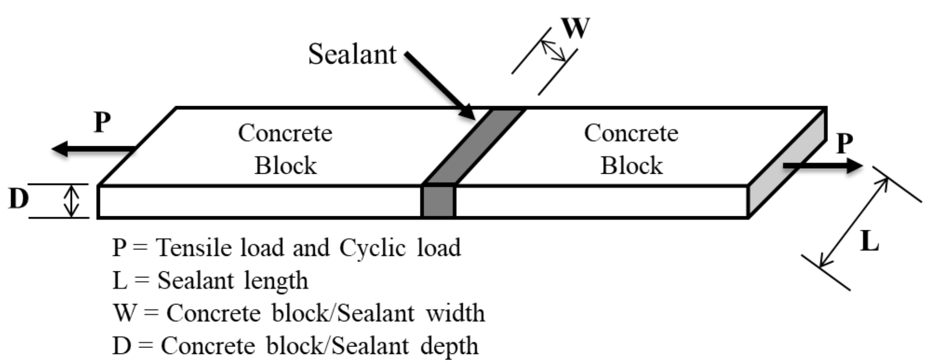


Figure 5.7. Tension test specimen.

Table 5.1. Typical Properties of DOWSIL 888 (Non-sag)

Application Temperature Range	-29 to 49 °C
Elongation	> 1000 %
Full Adhesion Time	14 to 21 Days
Modulus @ 150% Elongation, maximum	0.193 MPa (28 psi)

The concrete block thicknesses (D) ranged from 0.25, 0.375, and 0.75 in. with a length (L) of 3 in. The dimensions of the joint sealant are given in Table 5.2. The effects of the DoC on the geometry of each specimen were tested with a DoC of 0 to a maximum of 0.5. Case studies of unsymmetrical sections were also conducted.

Table 5.2. Test Specimen Specification.

SF (W/D)	Width (in.)	Depth (in.)	DoC
NS*- SF 1.5	0.375	0.25	0, 0.25, 0.5, US**
NS - SF 1.0	0.375	0.375	0, 0.25, 0.5
NS - SF 0.5	0.375	0.75	0, 0.25, 0.5, US
NS - SF 1.0-N***	0.25	0.25	0, 0.5
NS - SF 0.7-N	0.25	0.375	0, 0.5
NS - SF 0.3-N	0.25	0.75	0, 0.5

**Non-sag (NS), DOW 888,*
*** Unsymmetrical section (US)*
**** Narrow (N)*

5.5.4. Tensile Strength Test

An Instron tensile tester (Model 5943) was used for the sealant tensile tests. The pure sealant tensile test (stress-strain result) was conducted to provide a better understanding of the mechanism and stress development for joint test results as shown in Figure 5.8.

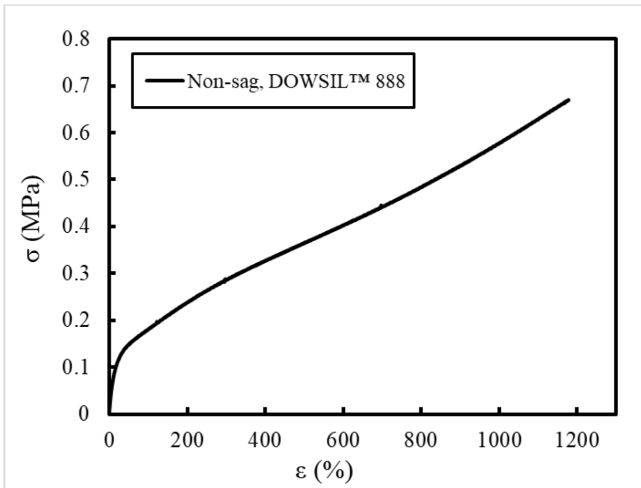


Figure 5.8. The stress-strain result for the pure sealant tensile test.

Test specimens were placed in the grips of the testing machine, using care to adjust them symmetrically to distribute tension uniformly across sealant cross-sections (draw a line on the concrete block to check that it is perpendicular to the grip as shown in Figure 5.9 (a)). The specimens were pulled at a constant crosshead velocity of 0.33 in./min until failure occurred. “Failure” referred either to a tearing apart of the sealant material (cohesive failure) or detachment of the seal from the concrete block substrate (adhesive failure) as shown in Figure 5.9 (b).

(a)

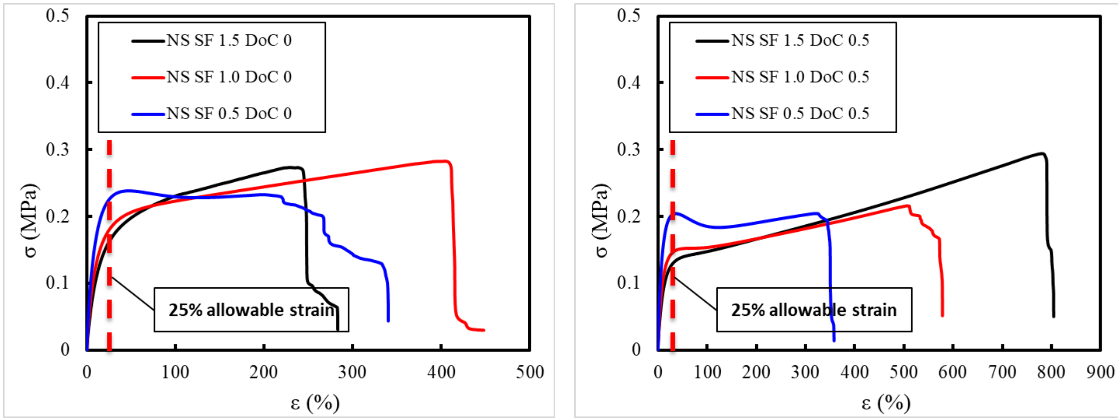
(b)

Figure 5.9. (a) A line on the concrete block to check symmetrically gripped (b) detachment of the seal from the concrete block substrate.

5.5.5. Test Results for Shape Factor and Degree of Curvature

The results (joint width: 0.375 in.) of the stress-strain laboratory tensile testing with three different SFs and a DoC of 0 are shown in Figure 5.10(a). The nominal maximum stress of the sealant varied from 0.23 to 0.26 MPa. With respect to the SF, there were no significant differences in the magnitudes of the ultimate tensile strengths, but the stress-strain curves differed significantly for all specimens. In the case of an SF of 0.5 (i.e., a thicker cross-section), the maximum stress occurred at an initial 40% strain and the specimen gradually failed without strain hardening. This shows that the tensile stress becomes more critical in deeper sections which result in premature yielding.

SFs of 1 and 1.5 showed a hyper-elastic curve shape (see Figure 5.4), the typical stress-strain curve of a silicone sealant in early stage. The magnitude of the stress could be reduced by increasing the SF for the 25% allowable strain. However, in sections where the SF value was 1 or 1.5 and the DoC 0, there were limitations (such as not perfectly manifesting hyper-elastic stress and strain) in terms of minimizing the occurrence of stress between the joint reservoir and sealant.



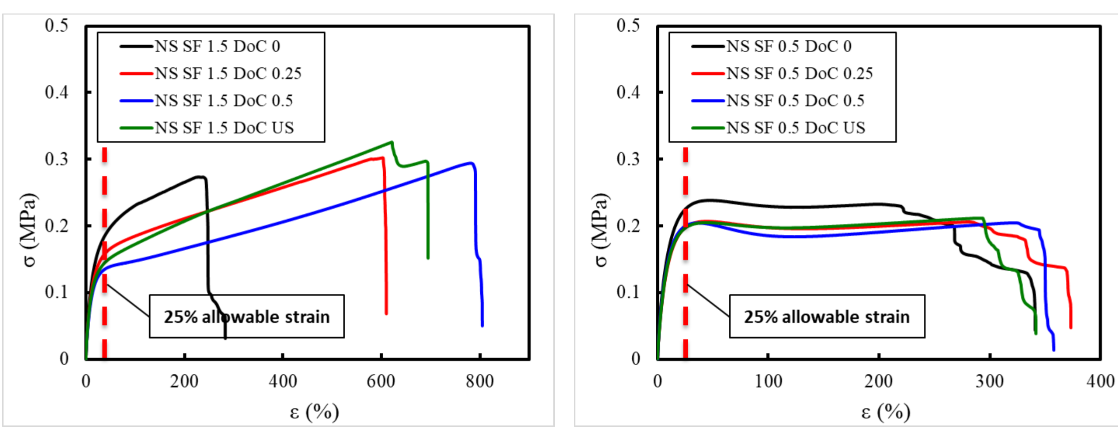
(a) DoC = 0 *(b) DoC = 0.5*

Figure 5.10. Tensile test results (joint width: 0.375 in.) for different SFs

Three different SFs and a DoC of 0.5 showed a maximum stress ranging from 0.2 to 0.27 MPa as shown in Figure 5.10(b). The stress-strain curve for a DoC of 0.5 showed a similar trend to that of a DoC of 0. As DoC increased from 0 to 0.5, SF 1 and 1.5 specimens significantly increased their ultimate stains and reduced stress values at 25% of the allowable strain. However, SF 0.5 samples had little effect on the changes in the ultimate strain and the stress values at the allowable strain as DoC increased. For SF 1.5, the specimen in DoC 0.5 failed earlier than SF 1.0. The cause is believed to be an early failure due to contamination of the concrete surface of the Vaseline, which was used to manufacture process. Therefore, SF 1.5 significantly increased the final staining from around 300% to 800% over other cases. In addition, the stress deformation curves for SFs of 1 and 1.5 were completely hyper-elastic at DoC 0.5. This behavior was similar to what was seen with the pure tensile test of the joint sealant as shown in Figure 5.8, in which the maximum stress occurred in the joint sealant material itself.

Figure 5.11 shows the test results when the 1.5 and 0.5 SF specimens had different DoC values. In the case of an SF of 1.5, Figure 5.11(a) shows a maximum tensile stress value ranging from 0.28 to 0.3MPa with a strain greater than 600%, except for the section with a DoC of 0. In addition, the section with a DoC of 0.25 and the unsymmetrical section had similar test results. Thus, when a curve was formed on a subsequent section by a backer rod in the joint sealant, bond stress between the joint reservoir and joint sealant was reduced for the SF of 1.5. The location where the maximum stress occurs due to the curve of the cross-section (hourglass section) was shown to be moved from the contact surface with concrete to the center of the sealant [7].

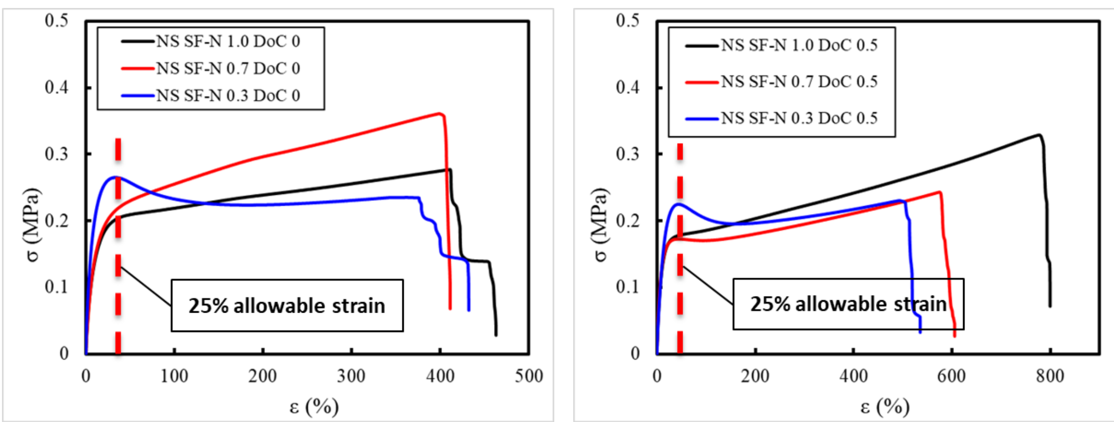
When the SF was 0.5, the benefits offered by the DoC were insignificant, as shown in Figure 5.11(b). All specimens showed joint sealant yield at a strain of about 30%. Regardless of the DoC, the joint sealant failed from the shear stress between the joint reservoir and sealant in cases of thick cross-sections (i.e., an SF value of 0.5). The reason is that the effect of DoC goes beyond the effect of significant shear stress on the section being in contact with concrete in the thick section [28].



(a) SF = 1.5 *(b) SF = 0.5*

Figure 5.11. Test results (joint width: 0.375 in.) for effects of DoC.

Figure 5.12 shows that the stress-strain results (joint width: 0.25 in.) with three different SFs and DoC values of 0 and 0.5 shared a similar trend with 0.375 in. sections (see Figure 5.10). The stress of the joint sealant decreased as the SF increased at a 25% allowable strain, as shown in Figure 5.12(a). For sections with SF of 0.3, due to substantial shear stress in thick cross-sections similar to sections 0.375 in. width, debonding between the joint reservoir and the joint sealant is observed at the limit of the allowable strain, despite the curved sections (DoC 0.5) as shown in Figure 5.12 (b).

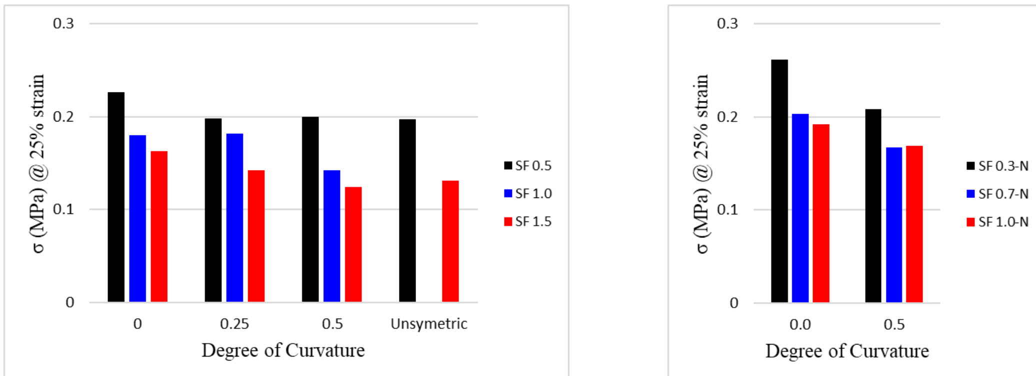


(a) DoC = 0 *(b)DoC = 0.5*

Figure 5.12. Test results (joint width: 0.25 in.) on the effects of SF.

Figure 5.13 shows the stress values of each specimen at the allowable strain (manufacturers recommend ideally 25% strain [3]). The joint sealant stress continues to decrease within the range of allowable strain as SF increases. As the section DoC increases, the joint sealant stress also decreases. The joint sealant stress is minimized when SF is 1.5 and DoC.is 0.5. The unsymmetrical cross-section resulting from the installation of the backer rod was also effective at reducing stress levels. The joint with

0.25 in. width also significantly reduces stress within the 20% allowable strain as SF and DoC increase.



(a) Joint width = 0.375 *(b) Joint width = 0.25 in.*

Figure 5.13. Stress values at an allowable strain of 25% and different joint width

5.6. Discussion

The literature review showed that narrower joint widths reduce noise generation. However, existing joint sealant design guidelines (joint depth related SF, recessed configuration, and surface treatment) may have limitations with respect to the current preferred joint width.

Stresses resulting from inappropriate SF values do not cause immediate failure of joint sealants, but can significantly change their life expectancy (cycles of failure are decreased), depending on the stress values generated (as shown in Figure 5.14) [78]. However, in case of the NS sealants that can be curved at the section tops and bottom, the experiment results showed that more extensive SFs (less than SF 1) could be used because stress generation can be reduced through an appropriate DoC.

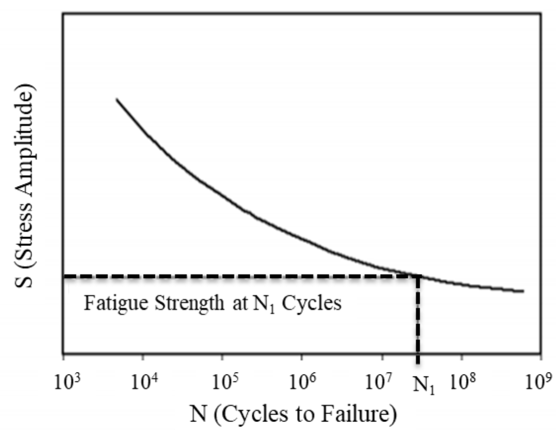


Figure 5.14. S-N curve for rubber.

Theoretically, in the simple tension and compression test, rubber-like material can be repeated indefinitely without permanent deformation within the extremely large strain (see Figure 5.4, 100 to 700%). However, since joint sealants behave in combination with concrete blocks, failures often occur on the bonded interface of concrete and sealants. In order to effectively maintain the lifespan of a joint sealant, the application of a DoC criteria should induce hyper-elastic behavior, so that no significant permanent deformation between joint reservoir and sealant occurs within allowable strain [27].

Although the hourglass shape (with a proper DoC) is ideal, it is impractical with SL silicone and hot-pour sealants because additional tools are needed to form a curved surface. For form-in-place (liquid) sealants, design elements (such as joint width, SF, and surface treatment) should be defined by distinguishing between NS silicone sealants capable of surface treatment and SL silicone (which is not required the surface treatment). The results of investigating the effect on DoC showed that joint sealants designed with an appropriate DoC can reduce stress level between the joint reservoir and sealant. In contrast, filled joints (Figure 5.2) are very susceptible to yielding at a small deformation, as the joint can only be rectangular sections with large SF and DoC of 0.

Conceptually, NS silicone sealants can effectively maintain curves at both the top and bottom of the sealant cross-section. SL and hot sealants can be installed with curved section at the bottom by using a backer rod but are often installed with a flat surface due to their ultra-low modulus. In practice, lower installation costs that can be achieved by simply filling a joint without using a backer rod. However, even with hot-pour sealants that have no choice but to flatten the above-section finish, curves below sections and proper SFs will have a positive effect on reducing stress.

5.7. Closing Remarks

As a narrow joint width is preferred for noise reduction, design practices for conventional joint sealants present geometrically related potential short comings due to improper joint width, joint sealant depth, and curvature. This study examined various combinations of these dimensions experimentally to elucidate their effects on stress levels in the joint sealant. Comparisons of all sections were made on the basis of changes to joint width, SF, and DoC. Based on the results presented here, the following conclusions can be drawn:

- The stress of the joint sealant decreased as the SF increased. A proper guideline of SFs is necessary. However, in the case of a rectangular section (i.e., a DoC of 0), there was a limit to the hyper-elastic behavior due to the occurrence of stress between the joint reservoir and joint sealant.

- As a result of the testing, increasing the DoC will reduce stress. However, the DoC will have little impact on a low-SF (i.e., thick) section due to shear stress effects caused by thick sections.
- Ultra-low modulus sealants (i.e., SL silicone and hot-poured material) with a DoC > 0 yields lower stresses than rectangular (i.e., a DoC of 0) sections if a backer rod is used. Thus, even in a narrow-width joint, a backer rod should be installed to ensure a proper SF and curve below the section.
- For NS silicone sealants, curves at the bottom and the surface can effectively reduce stress levels.
- The proper design of joint sealants can reduce joint sealant failures and maintain (or even improve) the service life of concrete pavement.

6. INVESTIGATION AND EVALUATION FOR THE BEHAVIOR OF JOINT SEALANTS ON CONCRETE PAVEMENTS WITH MOISTURE

6.1. Section Summary

Joint sealants play an important role in maintaining concrete pavement. They reduce or prevent numerous distresses, including spalling, faulting, and subbase erosion damage. Therefore, the successful maintenance of such joint sealants is closely linked to a satisfactory lifespan of rigid pavement. However, it has been found that many sealants often fail in the early stages, due to inadequate or insufficient joint preparation. This study examines the effects of moisture content on bond strength, the main cause of joint sealant failure. Sealant use in various climatic regions throughout the United States was examined, Departments of Transportation were surveyed with regards to how they handled moisture. The survey showed that in cold-freeze areas, hot-pour sealants are preferred over silicone. Most states visually inspect the moisture condition of joint reservoirs. This research evaluates the effects of surface moisture on the tensile bond strength between a joint sealant and reservoir. In addition, an indirect measurement method was applied to estimate the reduction in bond strength in response to excessive moisture on the reservoir wall, at the allowable strain. The causes of degradation in adhesion strength were evaluated by measuring the sealant wetting angle. Finally, it was determined that the choice of sealant may depend on the climate. Those not currently preferred in wet-freeze regions could be used if accompanied by proper pretreatment and moisture control, contributing to the stable lifespan of joint sealants and concrete pavement alike.

6.2. Current Joint sealant practice

A survey was prepared to investigate joint sealant practices in the United States (see Figure 6.1). The composition of the questionnaire was configured such that joint sealant practice and performance in different states would be reflected, providing insights into how the two might be related. The joint sealant design itself is important, but joint preparation is also believed to have a significant effect performance-wise, especially if the sealant suffers from a reduction in bond strength.

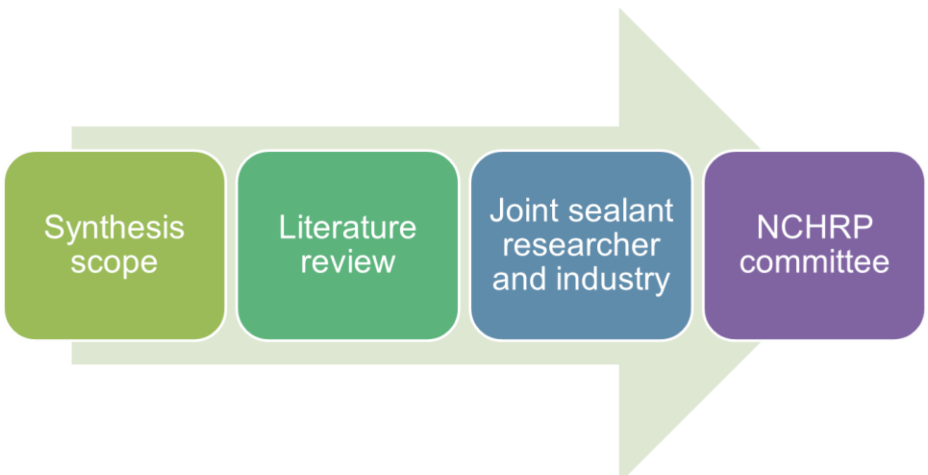


Figure 6.1. Questionnaire development process.

Survey questions were developed to meet the synthesis scope described below. Questions queried respondent on:

- Whether or not PCC pavement joint sealants were used,
- The types of materials used for PCC pavement joint sealants, and
- Constructions methods used for PCC pavement joint sealants.

A draft of the questions was drawn up with the goal of identifying current joint sealant practices. After a literature review, the detailed questions were finalized to address the synthesis scope. Further details were supplemented by the literature review and current standard specifications. Questions were also developed to identify potential problems in joint sealant practices and determine how DOTs solve them.

The questionnaires were distributed to experts on joint sealants and industry distributors, in order to gather their feedback on the topic. During this period, many discussions were had, and corrections made. The confirmed questions were also commented upon by the National Cooperative Highway Research Program (NCHRP) committee. Then, the joint sealant experts, related researchers, and NCHRP committee members again reviewed the survey to determine whether it was appropriate for identifying the current status of and potential problems with joint sealant use. The results of the survey produced noticeable results related to the effects of moisture and temperature on joint sealants based on climate region; consequently, the analysis was focused there.

Forty-one out of 50 states (82%) responded to the questionnaire, as shown in Figure 6.2. Thirty-two states (78%) out of the responding 41 used joint sealants, while the other nine said they used alternatives to joint sealing (six states) or did not use concrete pavement (three states). The nine states indicating that they did not use joint sealants were in the northern freeze area.

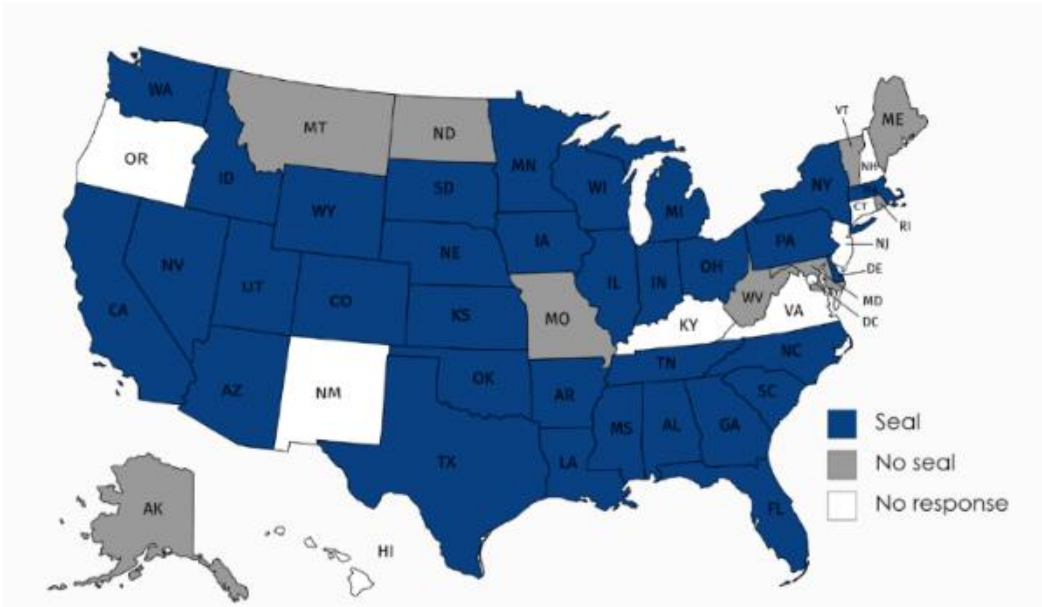


Figure 6.2. US map of joint sealant use in concrete pavement.

The United States is divided into four major climatic regions, as shown in Figure 6.3. Climate-specific analysis of the use of joint sealants showed that in most non-freezing areas, both silicon and hot-pour sealants were used. In the cold north (both dry and wet-freeze areas), there was a wide variety of responses regarding the sealant being used. All nine states that responded "no sealing" were in freeze areas (Figure 6.4 (a)).

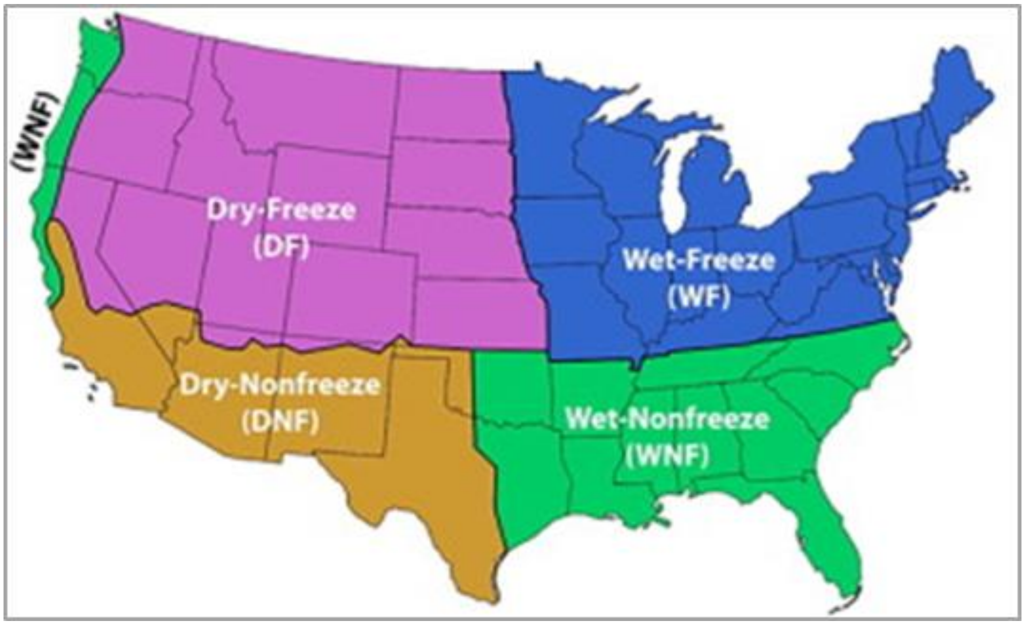
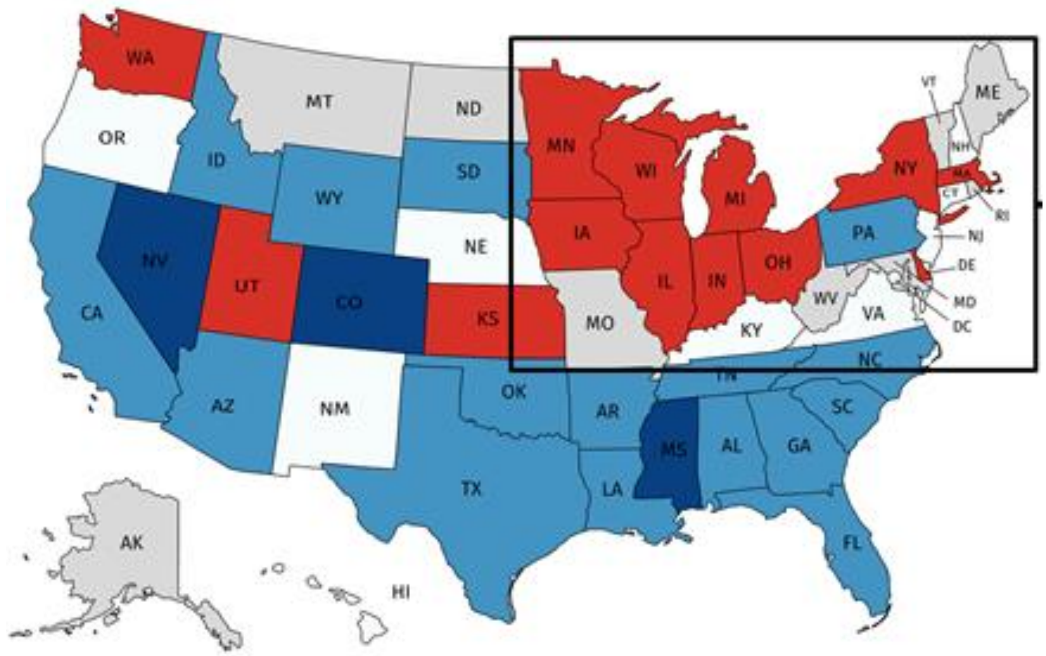


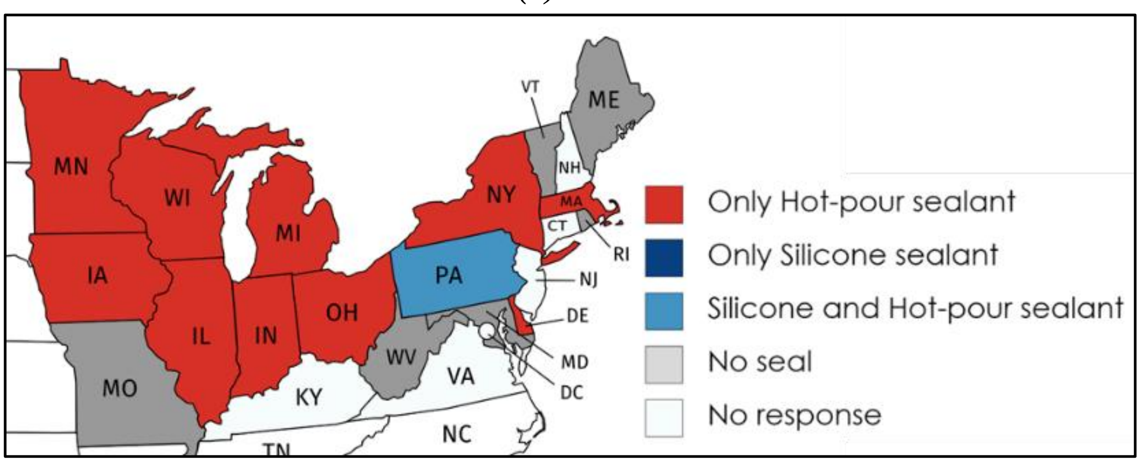
Figure 6.3. Four US climate regions [79].

Even in the same freeze area, especially in wet-freeze regions (23 states), most states (except for one) did not seal joints or only used hot-pour sealants, as shown in Figure 6.4 (b). In other words, silicon sealants were rarely used in wet-freeze regions.

The results of the survey showed that the joint sealant preferred depended on climate zone, especially in wet-freeze regions. It was important to address why silicon sealants are not preferred in this area and explore the adhesion strength according to moisture content. In addition, according to the survey, most states (23 states out of the 32 states using joint sealants, or 72%) attempted to manage moisture in joint reservoirs, but mostly only by visual inspection. Visual inspection does not allow for a proper evaluation of adequate moisture content. If moisture has a significant effect on the life of a sealant, the correlation between inspection method and adhesion strength must also be established.



(a) USA



(b) Wet-freeze area

Figure 6.4. Current joint sealant types used

6.3. Preparation for moisture examination

6.3.1. Test conditions and preparation

The tensile bond test specimen (see Figure 6.5) consisted of two concrete blocks that allowed the walls to form a bond with the sealant. Dow 888 (silicone, Figure 6.6 (a)) and

Crafco Roadsaver222 (hot-pour, Figure 6.6 (b)) sealants were installed between two concrete blocks horizontally facing a sawcut section.

Table 6.1. Typical Properties of DOWSIL 888 (Non-sag)

Application Temperature Range	-29°C to 49°C
Elongation	> 1,000 %
Full Adhesion Time	14 to 21 Days
Modulus @ 150% Elongation, Maximum	0.193 MPa (28 psi)

Table 6.2. Typical Properties of Crafco Roadsaver222

Application Temperature Range	-28°C to 70°C
Bond, -20°F (-29°C), 50% ext.	Pass 3 Cycles
Resilience	60% Minimum
Softening Point (ASTM D36)	80°C (176°F) Minimum

The dimensions of each concrete block were as follows. The depth was 12.7 mm (0.5 in); the concrete width was approximately 76.2 mm (3 in) and length was 50.8 mm (2 in). The dimensions of the sealants were a depth of 12.7 mm (0.5 in), width of 12.7 mm (0.5 in), and length of 76.2 mm (3 in).

The moisture content of the concrete blocks was varied to achieve different moisture contents, prepared as follows: OD) dried in the oven, ND) dried at room temperature, W) placed into water and fully saturated (approximately a 5% moisture content), DF) dried at room temperature and stored in a freezer, and WF) placed in water and stored in a freezer. The concrete blocks at specific moisture levels were wiped with a clean, dry, lint-free cloth prior to sealant placement. The concrete blocks were immediately sealed under specified conditions. Thirteen test specimens were prepared for testing at different moisture and temperature levels.

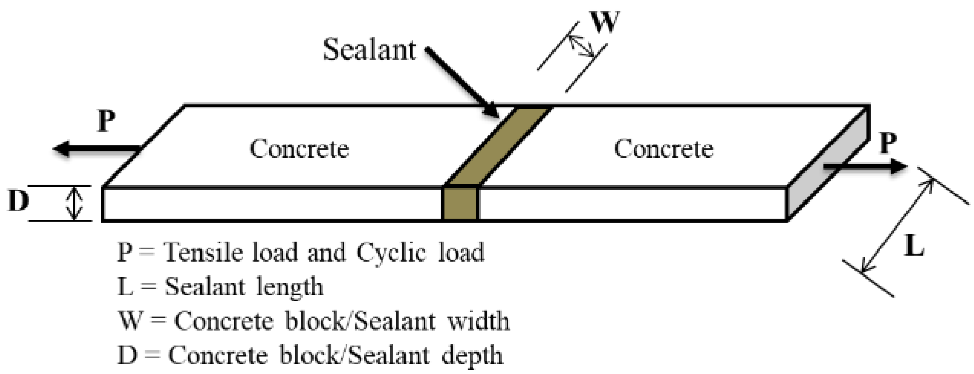


Figure 6.5. Tensile bond test specimen schematic.

6.3.2. Bond testing equipment and materials

An Instron tensile tester (Model 5943) was used for tensile bond testing. The machine was capable of producing uniform rates of grip separation varying from 0.05 to 2500 mm/min. Each test specimen was placed in the grips of the testing machine, using care to adjust the specimen symmetrically and distribute tension uniformly over the sealant cross-section. The specimens were then pulled at a constant crosshead velocity of 100 mm/min (nominal strain rate of 0.066 in $s{-1}$) until a failure occurred. Failure referred either to a tearing in the sealant material (i.e., cohesive failure) or detachment of the seal from the concrete block substrate (i.e., adhesive failure).

(a) Tensile bond test *(b) Silicone hot-pour sealant*

Figure 6.6. Test setup and specimens.

Depending on the sealant type, the concrete blocks were prepared into OD, ND, DF, or WF, according to the water and curing temperatures, and made into square sections (shape factor: width/depth = 1.0). The specifications of the test specimens are given in Table 6.3.

Table 6.3. Test Specimen Specifications

<table>
<tr><th>SF (W/D)</th><th>Material</th><th>Surface Condition</th><th>Specimen Number</th><th>Shape Factor</th></tr>
<tr><td>S-SF1-OD</td><td>DOW888 (silicone)</td><td>dried in oven</td><td>2</td><td rowspan="7">1.0</td></tr>
<tr><td>S-SF1-ND</td><td>DOW888 (silicone)</td><td>natural dry</td><td>2</td></tr>
<tr><td>S-SF1-W</td><td>DOW888 (silicone)</td><td>wet (saturated)</td><td>2</td></tr>
<tr><td>HP-SF1-ND</td><td>Crafco Roadsaver222</td><td>natural dry</td><td>1</td></tr>
<tr><td>HP-SF1-W</td><td>Crafco Roadsaver222</td><td>wet (saturated)</td><td>1</td></tr>
<tr><td>HP-SF1-DF</td><td>Crafco Roadsaver222</td><td>natural dry → freeze</td><td>1</td></tr>
<tr><td>HP-SF1-WF</td><td>Crafco Roadsaver222</td><td>wet → freeze</td><td>1</td></tr>
</table>

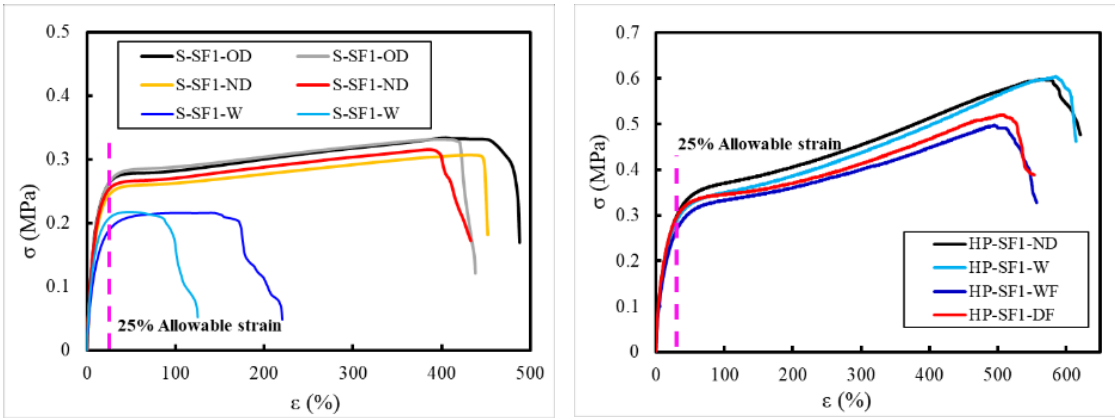
6.4. Test Results

6.4.1. Laboratory tensile bond testing

The stress-strain behaviors of the silicone sealant in response to various moisture levels under three different joint reservoir conditions were explored by a tensile bond test conducted at room temperature (~25°C). The nominal ultimate stress for the sealant varied from 0.2 to 0.35 MPa (29 to 51 psi). The sealants were observed to follow similar stress-strain patterns but showed a significant difference in the magnitude of the tensile stress with respect to moisture content, as shown in Figure 6.7 (a). Cohesive failure (i.e., failure within the material) was not observed to be dominant for any level of moisture content.

In the silicone sealant samples, the stress and strain of wet cases (S-SF1-W) were found to be significantly reduced compared to those dried in the oven (S-SF1-OD) and naturally dried (S-SF1-ND). In particular, the stress reduction was significant in relation to the allowable stress and strain (25%), showing that the moisture content of concrete affects the adhesion strength between concrete and a sealant, leading to early failure.

The effects of moisture level and temperature on the stress-strain behavior of hot-pour sealants under four different joint reservoir conditions was observed by applying a tensile bond test at room temperature (~25°C). The nominal ultimate stress when installing concrete (as related to moisture content and temperature) ranged from 0.45 to 0.6 MPa (65 to 87 psi), as shown in Figure 6.7 (b). Adhesive failure (failure between the concrete and sealant interface) was observed to be the dominant failure mode for any level of moisture content.



(a) Silicone *(b) Hot-pour sealant*

Figure 6.7. Tensile bond strength test results

In the case of hot-pour sealants, both stress and strain were unaffected by the moisture content of the concrete. However, when sections of the concrete blocks were frozen, the adhesion strength of both the wet (HP-SF1-WF) and dry (HP-SF1-DF) samples tended to decrease by 20%. However, there was no significant stress reduction at a generally acceptable stress-strain (25%).

As a result of the tensile bond experiments, the silicone sealant was found to be more likely to be affected by moisture than was the hot-pour sealant. This result matches what was found from the survey results from wet-freeze regions. In current joint preparation procedures, hot-pour sealants are better able to maintain a stable life expectancy in wet-freeze regions than are silicone sealants.

6.4.2. A non-destructive method of moisture measurement

The measurement of surface moisture under field conditions has its challenges, especially due to the configuration and width of joint sealant reservoirs. The current method of joint reservoir moisture detection is visual inspection. General quality control tests for joint reservoir moisture conditions are currently in development [2]. These methods are not yet credible, however, when it comes to ensuring appropriate moisture levels for sealant installation.

In the present research, it was assumed that moisture in the test blocks was uniformly distributed. Thus, measurement of the moisture content of the outer surface of the concrete blocks near where the sealant bonded to the wall was of primary interest. Ultimately, it is necessary to identify non-destructive methods for measuring water content throughout full sections of concrete blocks. Thus, indirect methods using microwave technology (i.e., a percometer) are very promising for the determination of moisture levels under field conditions.

In this study, the dielectric constant (DC) value was measured by direct contact with the top surface (instead of the reservoir wall) with the surface probe of a percometer, as shown in Figure 6.8.The dielectric value served as an indicator of the volumetric moisture content within the concrete [80]. The moisture content of the concrete test blocks was varied to achieve different moisture contents. These were prepared according to the following procedure: 1) oven dried to 0% , 2) placed in water and fully saturated (with different moisture levels for each block), and 3) dried at room temperature, followed by measurement of the weight of the block to obtain the specified moisture content.

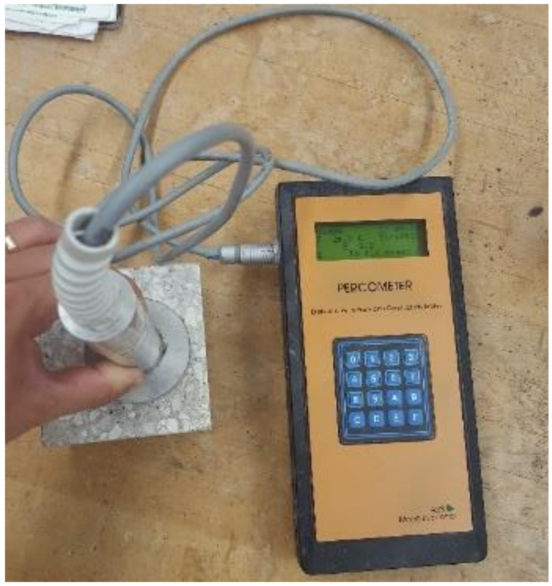


Figure 6.8. Measurement of DC.

The concrete samples used for this curve were fully hydrated and hardened. A study conducted by Lee and Zollinger developed a volumetric approach to determining free water content in PCC, based on dielectric measurements [65]. The moisture content was obtained by Eq. (4.3). However, similar to the approach presented in this research, their study was applicable to fresh concrete still forming a hydration reaction.

Figure 6.9 shows a comparison of the results of these two models for determining concrete moisture content and corresponding DC measurements. A calibration curve was developed to establish a relationship between the DC and free water content. Moisture content by weight was given by

$$MC(\%) = 6.28 \times \ln(DC) - 10.52 \tag{6.1}$$

where *MC*(%) = moisture content by weight; and *DC* is the dielectric reading measured by the percometer.

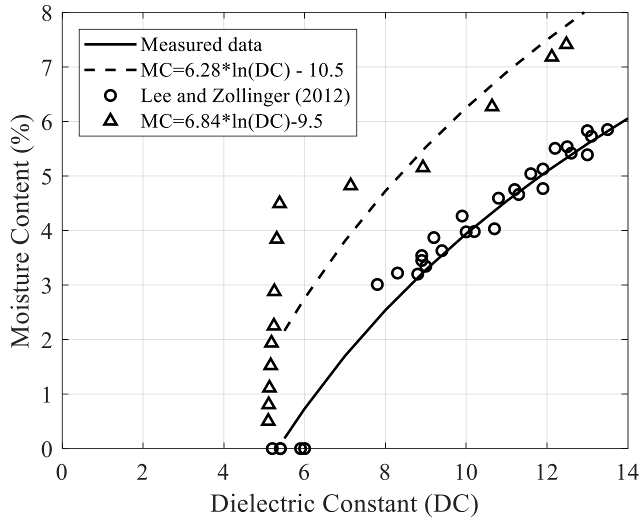
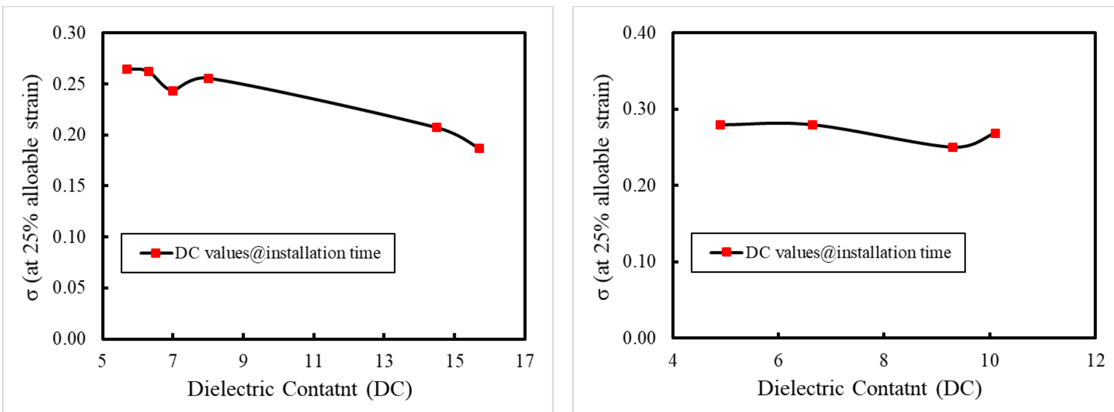


Figure 6.9. Relationship between moisture content and DC.

There was a constant difference between the moisture content levels obtained from the two models, attributable to different lengths of hydration time. It was determined that the model presented in this study can be used to measuring reservoir moisture after curing concrete, making it possible to estimate moisture content simply and quickly, based on the DC trend line.

As shown in the survey results, hot-pour and silicone sealants are used throughout the US, except in wet-freeze regions. In such regions, the use of silicone sealants is limited by the high moisture and low temperatures. However, if constructed properly, silicone sealants can offer various advantages, such as durability, excellent bonding with concrete, and good adhesion in general.

Using the model proposed, it is possible to predict adhesion strength through the indirect measurement of moisture content and determine moisture treatments for surfaces affecting adhesion. In the case of silicone sealants, as shown in Figure 6.10 (a), the stress value decreases due to failure of the attachment between the joint sealant and concrete; this is attributable to the moisture at the allowable strain as the DC value increases. Hot-pour sealants (Figure 6.10 (b)) have little effect on the relationship between bond stress and DC in joint reservoirs, regardless of moisture level.



(a) Silicone *(b) Hot-pour sealant*

Figure 6.10. Stress-surface moisture relationship (measured DC) at a 25% allowable strain.

6.4.3. Wettability

When an interface exists between a liquid and a solid, the angle between the surface of the liquid and outline of the contact surface is described as the contact angle θ (lower case theta) [81], as shown in Figure 6.11. The contact angle (or wetting angle) is a measure of the wettability of a solid by a liquid. Using the above relationship (i.e., formula), it is also a measure of adhesion work, which is related to adhesion ability.

The adhesion work (W_A) can be used to assess in thermodynamic terms the capacity of various bonding additives on the polymer surface. This can be calculated using the following formula [82]:

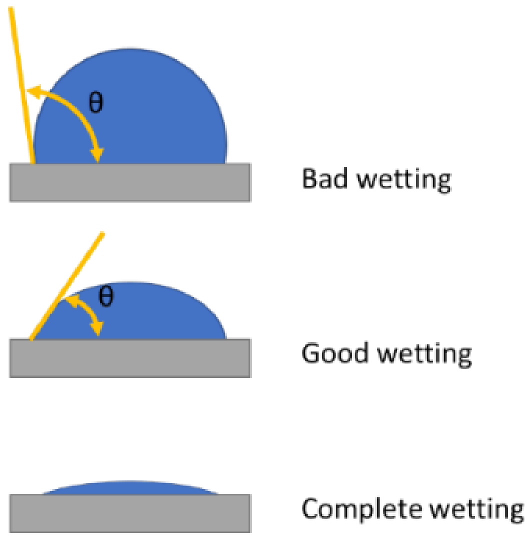
$$W_A = \gamma_{LV}(1 + cos\theta) \quad (6.2)$$

where W_A = adhesion work, θ = the contact angle; and γ_{LV} = surface tension of water at a specific temperature.

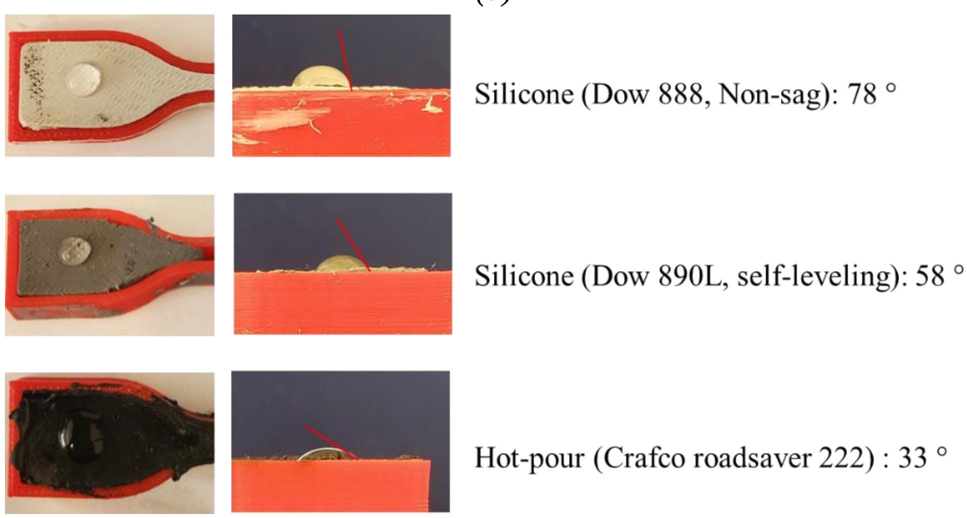
6.4.3.1. Contact Angle

The contact angle is a direct measure of wettability. It provides an effective means of evaluating many surface properties, such as surface contamination, hydrophobicity, energetics, and heterogeneity. When $\theta > 0$, the liquid is non-spreading and reaches an equilibrium position between the liquid-fluid and solid-liquid interfaces. When $\theta = 0$, the liquid wets without limit and spontaneously spreads freely over the surface. Hydrophobic surfaces repel water and produce high contact angles. Hydrophilic surfaces attract water and produce low contact angles.

With the measured contact (i.e., wetting) angles between a water droplet and substrates of two different types of silicone and hot-pour sealants, the adhesion work (W_A) can be calculated using the equation above. The surface tension of water in air is 72.0 mN/m at 25°C [83], the value at which all wetting angle measurements and tensile bond tests for the present research were run. As illustrated in Figure 6.12, the values calculated for the adhesion work of water on the Dow 888, Dow 890L, and hot-pour substrates were 86.97, 110.15, and 132.38 mN/m, respectively. The hot-pour substrate provided the most adhesion work of water, as compared to the two other silicone-based sealants. The hot-pour substrate showed a 52.2% adhesion work improvement as compared to the Dow 888 case, and a 20.2% improvement as compared to the Dow 890L case. Thus, of these three cases, the adhesion ability (i.e., adhesivity) of water is best with the hot-pour sealant.



(a)



(b)

Figure 6.11. (a) Dependence of the surface wettability on the contact angle and (b) sealant measurements.

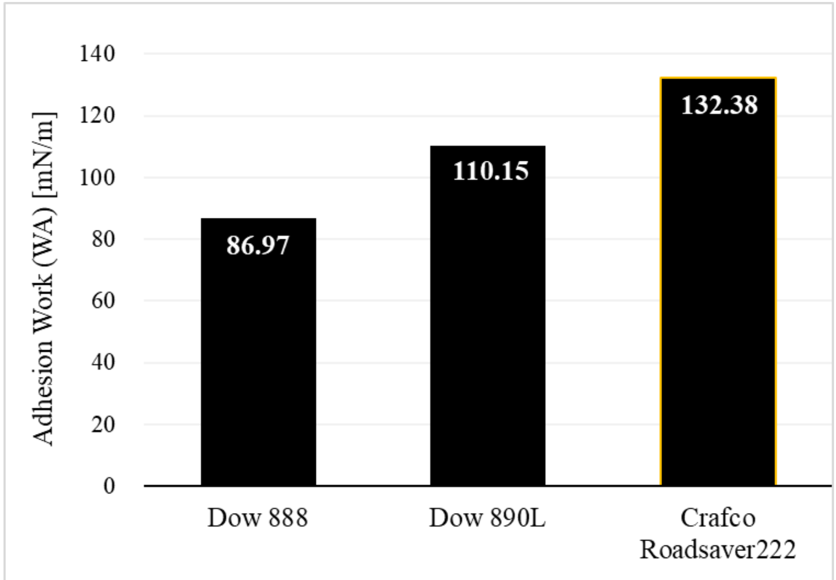


Figure 6.12. The adhesion work (W_A) of water on silicone-based and hot-pour substrates.

The outcomes of this comparative study on wettability and adhesion work show that the specific type of hot-pour sealant used in this experiment was more hydrophilic than the two silicone-based sealants, indicating it would be better for wetting water-coated or water-friendly substrates. This finding suggests that hot-pour sealants should be used in environments with high humidity.

The decrease in adhesion strength due to moisture in a sealant can be overcome by reducing the stress; this can be accomplished by designs with lower SF or larger degrees of curvature [7]. Also, silicone sealants can be used in wet areas if moisture effects are minimized by drying the reservoir wall before construction.

6.4.3.2. Temperature's Effect on the Surface Tension of Water

Surface tension is dependent on temperature. The effects of temperature on the surface tension of a water colloid in air have been thoroughly studied. The surface tension of water decreases significantly with temperature, as shown in Figure 6.13. Surface tension arises from the polar nature of the water molecule. In wet-freeze regions, the surface tension of water increases, so it is preferable for the adhesion work of water to be connected by surface tension [83].

Conventional construction sealants have shown various degrees of sensitivity to moisture. Hydrolysis causes the breaking of bonds within a sealant. Thus, the bond strength decreases and cohesive failure results. However, before hydrolysis is fully operational, the sealant may experience swells, deformation, or bond failure at the joint [44].

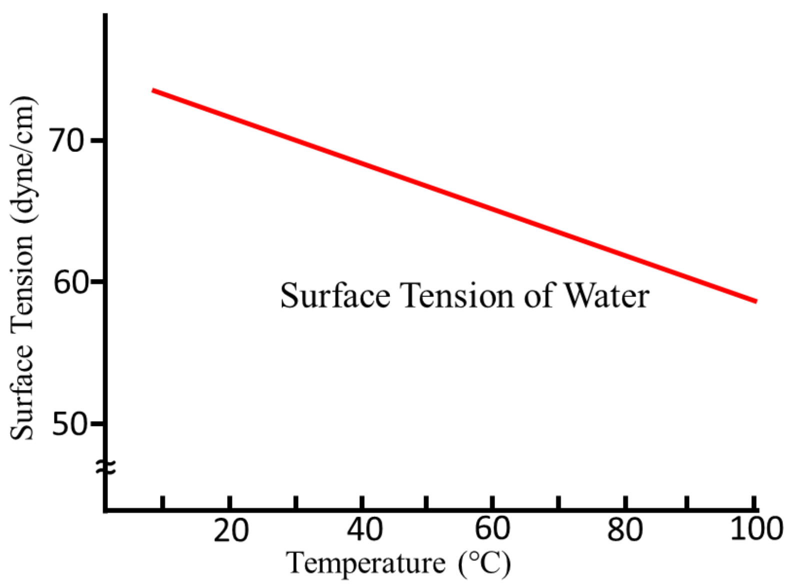


Figure 6.13. Changes in the surface tension of water due to temperature.

The results indicate that rising water temperatures reduce surface tension, allowing for better bonding to a solid substrate. Since moisture is an obstacle to concrete materials bonding with adhesives or sealants, moisture in cold environments deteriorates the adhesive properties of sealants. This finding correlates with the fact that hot-pour sealants with better adhesivity are preferred over other silicone-based sealants in wet-cold regions.

6.5. Closing Remarks

This research examined the effects of moisture content on the bond strength between joint sealants and concrete pavement. Based on the results presented here, the following conclusions can be drawn:

- This research studied the use of sealants in various US climatic regions and how DOTs measure moisture content on reservoir walls. A survey showed that silicone sealants were rarely used in wet-freeze regions; most agencies used hot-pour sealants or no sealant at all. Most states in the US visually inspect joint reservoirs to determine moisture content.
- The effects of surface moisture on joint sealants and reservoirs were evaluated by a tensile bond strength test. Tensile bonding experiments confirmed that silicone sealants are more affected by moisture content on a reservoir wall than are hot-pour sealants.
- An indirect method of moisture measurement can be used to estimate the reduction of bond strength in allowable strain due to excessive moisture.
- The causes of degradation in bond strength were evaluated by measuring the sealant wetting angle. Hot-pour sealants had the best adhesion because the angle was the smallest (according to the wettability measurement results). Therefore, even if water is present, hot-pour sealants can be used effectively in concrete reservoirs.

- As the temperature of water drops, the surface tension increases, preventing adhesion to solid substrates. Since moisture is an obstacle to concrete materials bonding with adhesives or sealants, moisture in cold environments weakens the adhesion properties. Thus, hot-pour sealants or no sealant at all are preferred in wet-freeze regions.
- Suitable joint preparation (or moisture control) or separately using a sealant (depending on the climate) will contribute to the stable lifespan of joint sealants and concrete pavements.

7. SUMMARY, CONCLUSIONS, AND FUTURE WORKS

7.1. Summery

The joint sealant has evolved in recent decades. As this evolution has progressed, joint sealant practices have changed. However, current practices and their respective performances have yet to be fully documented. Therefore, it is necessary to establish a standardized approach to joint sealant evaluation, as well as investigate and assess joint sealant practices in Portland cement concrete design.

Current joint sealants have been designed without consideration of the strength and shape of the bond between the concrete and sealant and its effect on stress concentration. This often resulted in adhesive failure within 1.5 years, much earlier than the expected service life of the joint sealant (20 years). Bond strength and stress on the interface between the sealant and joint reservoir face play important roles in adhesive failure. Therefore, in the present research, experimental bond tests and a finite element method (FEM) analysis were conducted to examine the nature of the bond at the sealant/joint reservoir interface. In addition, the stress distribution along the interface was also investigated by analyzing the geometric shape factor (SF), degree of curvature (DoC), and joint preparation conditions.

For this study, data was gathered through a literature review, survey of Departments of Transportation (DOTs), and subsequent discussions with selected agencies to determine case documentation practices. Re-evaluation of the SF was conducted, and a new design factor, DoC, was introduced and explored through the FEM and experimental analysis. With these factors, the bond strength reduction and increase in stress at the interface could be limited reducing the potential for early adhesive failure. This study examined the effects of moisture content on bond strength, the main cause of joint sealant failure. Sealant use in various climatic regions throughout the United States was examined, and DOTs were surveyed with regards to how they handled moisture.

As a result of this investigation, it became clear that some advances in the composition, design, and preparation of sealants, especially in terms of the design of and inspection methods for narrow joints, appear to conflict with established recommendations. It was also appeared that institutions lack the necessary tools and control protocols to facilitate the proper inspection of cleaning and joint preparation work. The effects of poor joint preparation (i.e., dirt and moisture) on joint strength and the shape of the joint sealant (i.e., SF and DoC) should be considered when designing and installing sealants. This research evaluated the effects of surface moisture on the tensile bond strength between a joint sealant and reservoir. The causes of degradation in adhesion strength were evaluated by measuring the sealant wetting angle. Finally, it was determined that the best choice of sealant may depend on climate. Those not currently preferred in wet-freeze regions could be used if accompanied by proper pretreatment and moisture control, contributing to the stable lifespan of joint sealants and concrete pavement alike.

7.2. Conclusions

In the present research, data were gathered and investigated through a survey of DOTs, with the goal of establishing standards for evaluating joint sealants in PCC pavement design. Based on the survey, the following conclusions could be drawn:

1. Of the 50 DOTs in the United States, 41 (82%) completed a joint sealant practice questionnaire. In response to questions about seal use, most states reported using joint sealants. Many employed joints narrower than conventional joint widths. The configuration and design criteria of the sealant according to this narrower joint width appeared to conflict with established recommendations from the ACPA.
2. Regarding the surface configuration of joint sealants, most states used silicone and hot-pour sealants with recessed surface treatments. In particular, hot-pour sealant use appeared to be at odds with the ACPA's recommendations, a conclusion requiring further investigation of the reasons supporting this practice and its effect on performance.
3. For most agencies, joint preparation involved a visual inspection. In addition, agencies appeared to lack the tools and control protocols needed to facilitate proper inspection of cleaning and other joint preparation work.
4. The principal distress type referenced in the survey responses was the premature failure of debonding. Early-stage failure stems from improper or insufficient joint preparation and design rather than the material itself. Therefore, DOTs should reconsider their design and joint preparation practices with regards to narrower joint widths.

5. Silicone sealants were rarely used in wet-freeze regions; most agencies used hot-pour sealants or no sealant at all. Most states in the US visually inspected joint reservoirs to determine moisture content.

Along with the survey results, this study both analytically and experimentally investigated the behavior of joint sealants. The following conclusions were drawn:

1. To prevent adhesive failure at an early age, the SF and DoC of the joint sealant need to be increased to reduce stress throughout the section and eliminate stress concentration at the interface between the sealant and concrete. Recession of the sealant at the top surface will not offset the effects of failing to include a backer rod in the joint reservoir. The asymmetrical sections currently used in the field to reduce road surface noise showed a stress concentration similar to a rectangular section. Therefore, an hourglass shape is recommended, as Tons [26] originally proposed. Both moisture and dirt on the interface between the concrete and sealant significantly decrease bond strength. Criteria for adequate joint preparation are needed to standardize the procedure, reduce early adhesive failure, and maintain (or improve) the service life of the sealant and concrete pavement.
2. The stress of the joint sealant decreased as the SF increased. However, in the case of the rectangular section (i.e., with a DoC of 0), there was a limit to the hyper-elastic behavior, due to the occurrence of stress between the joint reservoir and sealant. The test results indicate that increasing the DoC will reduce the stress. However, the DoC was found to have little impact on a low-SF (i.e., thick) section, due to the effects of shear stress caused by the thickness. Ultra-low modulus

sealants (i.e., SL silicone and hot-poured materials) with a DoC > 0 yielded lower stresses than did the rectangular sections (i.e., with a DoC of 0), if a backer rod was used. Thus, even in a narrow-width joint, a backer rod should be installed to ensure a proper SF and curve below the section. For NS silicone sealants, curves at the bottom and surface can effectively reduce stress levels. The proper design of joint sealants will reduce joint sealant failures and maintain (or even improve) the service life of concrete pavement.

3. The results of the tensile bonding experiment indicated that the silicone sealants were more affected by the moisture content on the reservoir wall than were the hot-pour sealants. The causes of degradation in bond strength were evaluated by measuring the sealant wetting angle. Hot-pour sealants had the best adhesion because the angle was the smallest (according to the wettability measurement results). Increases in the surface tension prevented adhesion to the solid substrate as the temperature of the water dropped. Moisture is an obstacle to concrete materials bonding with adhesives or sealants, and thus moisture in cold environments weakens adhesion properties. Therefore, even if water is present, hot-pour sealants can be used effectively in concrete reservoirs, and hot-pour sealants or no sealant at all are preferable in wet-freeze regions. Suitable joint preparation (or moisture control) or separately using a sealant (depending on the climate) will contribute to the stable lifespan of joint sealants and concrete pavements.

7.3. Future works

Based on the findings of this study, recommendations to extend the results include the following:

1. In joint reservoir design, joint width tends to be narrower than the design guidelines of the ACPA. With this trend, it may now be necessary to reassess sealant thicknesses and adherence to shape factors proposed by the ACPA for these narrower joint widths, in order to adequately ensure durability for the installation. Furthermore, the adequacy of current cleaning methods may also require reassessment.
2. Some state agencies indicated that they were moving away from the use of joint sealants. Closely related to this is a deficiency tied to the lack of data, tools, and resources needed for adequate materials selection for a given candidate joint sealing project. Decisions regarding the need for and type of sealant involve the sealant requirements as related to concrete pavement performance. Factors key to decisions of this type include details related to the jointing system of the pavement, traffic level, and type of subbase used below the concrete slab. In other words, a modeling tool is needed to ascertain joint sealing performance and the risks involved with not sealing.
3. Assessment of erosion potential will likely be key to the development of a tool for assessing the need for sealing and type of sealant that should be used for a given project. Such a tool would include factors such as traffic loading and frequency of loads, the existence of water and a pathway for the water to enter sublayers (i.e., the effectiveness of the joint sealant), and the material properties of the subbase.

Therefore, assessment of the erosion potential is key to a consideration of the relationship between sealant practices and pavement performance.

4. It is recommended that a long-term investigation into the performance and conditions of joint sealants be carried out, with the goal of developing the necessary data, tools, and resources, allowing agencies to make key decisions regarding the uses of joint sealants and thus realize their full benefit.
5. Joint sealant is a polymer with viscoelastic characteristics. Therefore, studies on performance experiments and analytical models of the behavior of materials including viscoelastic behavior are needed.

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